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WELDING OF STAINLESS STEELS

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TECHNICAL MEMORANDUM X-53576

WELDING OF STAINLESS STEELS

By

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ABSTRACT

The state of the art of the welding of stainless steels is reviewed. Welding preparations, specific welding processes, welding of dissimilar metals, and joint quality are discussed. The metallurgical factors involved when welding stainless steels are covered in terms of their metallographic characteristics, i.e.,: austenitic, ferritic and martensitic alloys. Methods of distortion control are discussed. The norifusion welding processes, solid state welding, brazing and soldering as applied to stainless steels are reviewed. An Appendix details the basic characteristics of several welding processes.

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PREFACE

This report is one of a series of state-of-the-art reports being prepared by Battelle Memorial Institute, Columbus, Ohio, under Contract No. DA-01-021-AMC-11651(Z), in the general field of materials fabrication.

It reviews practices for joining stainless steels. Discussions are presented to provide

(1) Information on joining preparations

(2) Information on joining processes

(3) Information on joint quality.

Techniques and special considerations that are normally followed when joining stainless steels are described.

The information covered was obtained from producers of stainless steels, equipment manufacturers, technical publications, reports from Government contracts, and from interviews with engineers employed by major fabricators and producers of these stainless steels. Data from reports and memoranda issued by the Defense Metals Information Center, and from International Institute of Welding reports, also were used. Experience gained during the preparation of previous reports in the series has also helped in the preparation of this report.

The literature search for this program began with 1955. In accumulating the information necessary to prepare this report, the following sources within Battelle were searched, covering the period January, 1955, to the present:

Defense Metals Information Center

Main Library

Slavic Library

Technical Journal Indexes for the period of 1955 to the present also were searched (Ref. 1), and information was obtained from sources outside of Battelle, viz., the Redstone Scientific Information Center (Refs. 2 and 3), the Defense Documentation Center (Ref. 4), and the NASA Scientific and Technical Information Facility (Ref. 5). Selected references published prior to 1955 were used also where these references contained basic information that has remained valid to the present time.

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WELDING OF STAINLESS STEELS

SUMMARY

Stainless steels can be joined by the commonly used fusion-welding processes, by brazing and soldering, and by solid-state joining processes. Usually, stainless steels are used in applications that require good corrosion resistance, strength and creep resistance at high temperatures, or toughness at cryogenic temperatures. These applications all require excellent quality of welded or brazed joints. High-quality joints can be obtained if close attention is given the details of the joining operation and approved practices are followed. Procedures for joining stainless steels are more critical than for carbon or low-alloy steel.

The specific welding practices to be used differ with the class of stainless steel - austenitic, ferritic, or martensitic being welded. The composition of the electrode or filler wire used in arc welding stainless steels must be matched to the base-metal composition to insure sound welds. Special precautions are required to preserve good corrosion resistance of the weld joints. The austenitic stainless steels are readily weldable by all processes. Welds in the ferritic and martensitic stainless steels tend to be brittle although ductility can be restored in martensitic stainless steel welds by heat treating. Careful prewelding cleaning procedures are required to prevent contamination of the weld joint. The precautions in brazing stainless steels are similar to the arc-welding precautions: careful cleaning, close control of the operation, and proper selection of the filler metal,

INTRODUCTION

Stainless steels are alloy steels that are characterized by their high degree of resistance to corrosion by a wide range of highly active solutions, acids, atmospheres, etc. This group of steels achieves this high resistance to corrosion by virtue of its high chromium content: between about 12 and 24 percent. Most of these steels also have excellent resistance to oxidation and scaling at high temperatures and retain good strength and creep resistance at much higher temperatures than do most other steels. At the opposite end of the temperature scale, certain of the stainless steel alloys have excellent toughness and ductility at very low temperatures - in the temperature range of liquid gases. In addition, most stainless steels are readily weldable.

This rather remarkable combination of properties has resulted in a broad range of applications for stainless steels. Stainless steels have come to be considered the standard material of construction in the chemical industry. Welded tubing, piping, and vessels in a broad range of sizes and shapes are made from various stainless steels. For cryogenic applications, stainless steel is unsurpassed. Storage vessels and transfer lines for handling liquid oxygen, hydrogen, etc. are fabricated from stainless steels. Ground support facilities for missile systems utilizing liquid oxygen require extensive stainless steel welded constructions. Missiles and space boosters use welded stainless steel piping systems for fuel and oxidizer. Nuclear reactors and power generators require stainless steel for structural service and heat-transfer loops. In addition, there is a broad usage of stainless steel in such fields as consumer products, automotive, food handling, steam power systems, etc.

There are three classes of stainless steels:

(1) Austenitic chromium nickel

(2) Ferritic chromium

(3) Martensitic chromium.

The class to which a particular stainless steel belongs is determined by its chemical composition. The composition of the steel, in turn, determines its metallurgical microstructure which is the distinguishing characteristic of each class. Techniques and processes for welding each class are similar.

Procedures for welding stainless steel have been developed and perfected over a period of some 40 to 45 years. Extensive utilization of stainless steels began around 1920 and the development of welding procedures began almost immediately. The study of welding problems and improvement of welding procedures still are being pursued today. However, procedures and materials have been developed to the point where few problems will arise in the welding of stainless steel providing close adherence to approved practices are followed. It is the purpose of this report to discuss these practices so that problem areas can be anticipated and avoided.

Procedures for welding stainless steel are more precise and critical than for welding carbon or most low-alloy steels. However, stainless steel is easier to weld than titanium and some of the nickel-base and superalloys. The important factors that must be considered in welding stainless steel are (1) composition of the base metal, (2) selection of the filler metal, (3) selection of the welding process, and (4) close adherence to established welding practices and techniques. Discussion of these factors is included in the various sections of this report.

MATERIALS

Stainless steels are a family of iron-base alloys having excellent resistance to corrosion and heat. They do not rust and strongly resist being attacked by a great many liquids, gases and other chemicals. Many of the stainless steels also have good low-temperature toughness and ductility. Stainless steels exhibit good strength properties and resistance to scaling at high temperatures.

TYPES AND PROPERTIES

Stainless steels are corrosion resistance because of their high chromium content. At least 11-1/2 percent of chromium is required to impart corrosion resistance. For better corrosion resistance more chromium usually is added with most stainlesssteels containing around 18 percent chromium.

Other alloying elements also are added to stainless steels (Ref. 6,7,8,9). In some cases, these other alloying elements impart still better corrosion resistance. In other cases, they improve formability, increase strength, or improve weldability. Nickel is the most commonly used additional alloying element in stainless steels.

Stainless steels are broadly divided into three groups according to their composition and metallurgical characteristics. These are:

(1) Austenitic chromium-nickel stainless steels

(2) Ferritic (nonhardenable) chromium stainless steels

(3) Martensitic (hardenable) chromium stainless steels.

The steels within each group display similar properties and welding characteristics although there are some individual differences. The compositions of the various stainless steel alloys are readily available in the literature. Room temperature and elevated temperature properties of stainless steels can also be found in the literature. Low-temperature properties of some of the austenitic stainless steels are shown in Figure 1, other data are found in the literature (Ref. 12).

The austenitic chromium-nickel stainless steels make up the largest and most commonly used group of stainless steels. All of the Type 200 and 300 series are in this class. Most of the stainless steels in this class are readily weldable by any arc or resistance-welding process. The Type 303, 303Se, and 347FSe are free-machining grades and are very seldom welded.

The ferritic chromium stainless steels include the alloys of the nickel-free 400 series of stainless steels that contain over about 14 percent chromium. Welds in these steels are brittle and have low-corrosion resistance in the as-welded condition. Annealing after welding is required to restore ductility and corrosion resistance.

Some of the 400 series alloys generally contain less than 14 percent chromium and more carbon than the ferritic steels. These are the martensitic chromium stainless steels. These alloys can be hardened by heat treatment.

METALLURGICAL FACTORS IN THE WELDING OF STAINLESS STEELS

In welding stainless steels it is essential to use methods which preserve their distinctive properties and high quality. Thus, weldments should be made which are adequate in soundness and strength, and retain a sufficiently high degree of corrosion resistance and good appearance, to meet the needs of the intended application. To accomplish these ends with success, it is necessary to have a knowledge of the metallurgical structure of stainless steels and of the structural changes which may occur when these steels are welded.

<u>Austenitic Chromium-Nickel Stainless Steels</u>. The chromium-nickel stainless steels have a microstructure which is composed essentially of the tough, ductile, nonmagnetic austenitic phase. Accordingly, these steels are called austenitic

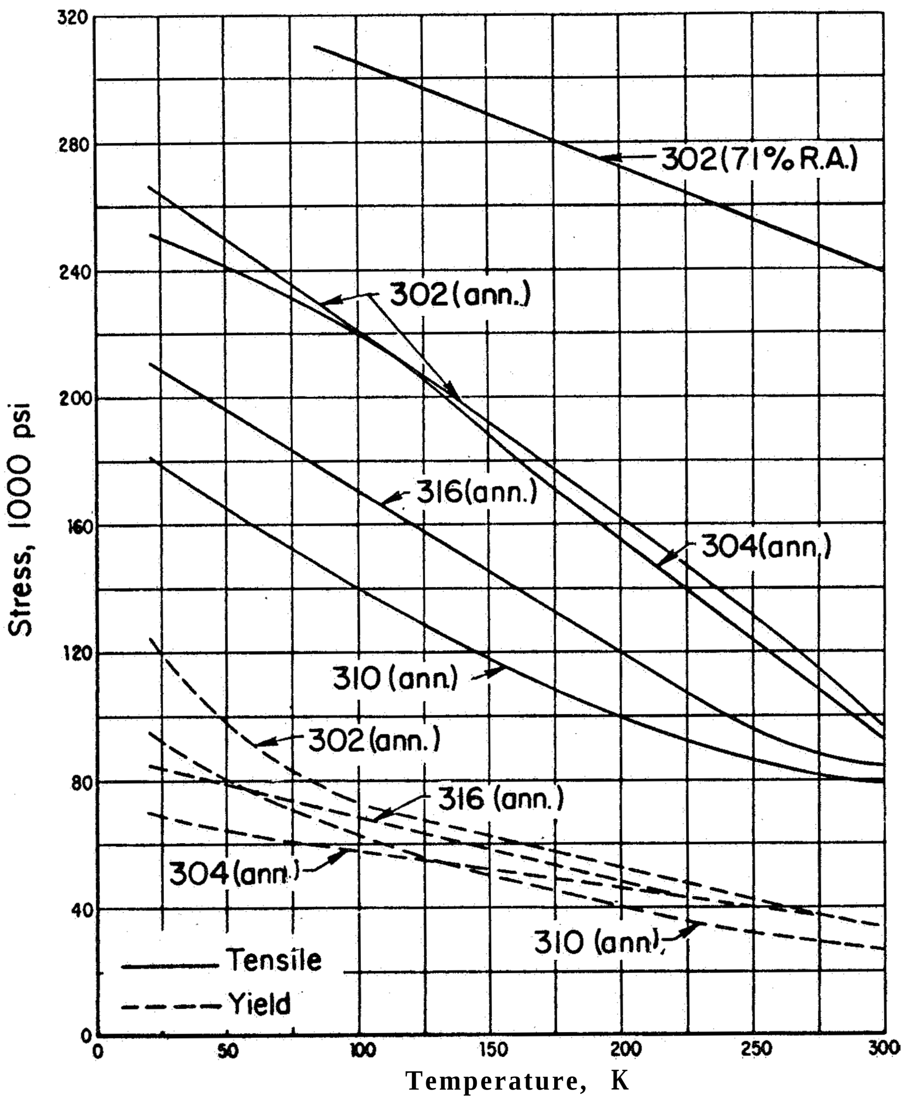


FIGURE 1. LOW-TEMPERATURE STRENGTHS OF SOME AUSTENITIC STAINLESS STEELS (REF. 13, 14)

stainless steels. However, a small amount of soft, magnetic ferrite, usually less than 10 percent, may be present in some types of austenitic stainless steels. The amount of ferrite in the structure depends largely on the balance achieved between those elements in the steel (i.e., carbon, nickel, manganese, nitrogen) that favor austenite formation and those that promote ferrite formation (i.e., chromium, molybdenum, silicon, columbium, titanium).

These steels retain their austenitic microstructure at all temperatures. This means that the chromium-nickel stainless steels cannot be hardened by heat treating. For this reason, this class of steels does not undergo any structural change during welding and the weld joints are tough and ductile as welded.

The metallurgical factors which will affect the quality of the austenitic stainless steel weld joints are as follows: (1) weld-metal and base-metal ferrite content, (2) carbide precipitation in the weld metal and heat-affected zone, (3) weld metal and heat-affected-zone grain growth, and (4) silicon content of the weld metal. With the proper understanding of the effects of these factors and method for their control, the welding engineer can specify welding procedures, welding materials and base materials which will effectively overcome the drawbacks caused by these various metallurgical factors. Each of these factors is discussed separately in the following sections.

Control of Ferrite Content. Fully austenitic weld deposits often tend to develop microcracks during welding. On the other hand, welds containing a small amount of ferrite are highly resistant to cracking. Therefore, good practice calls for selecting the composition of the filler metal, or electrode, so as to form an austenitic deposit containing a small percentage of ferrite. If the weldments are to be used at very low temperatures, the impact strength of the weld metal at the service temperature can be seriously impaired if the ferrite content becomes too high. For low-temperature service, the ferrite content of the weld metal should be in the range of 4 to 10 percent. The actual ferrite content of the weld metal depends on the composition of the base metal, the composition of the electrode or filler wire, and the extent to which the weld-metal deposit is diluted by the welded parent metal.

The Schaeffler diagram is a useful tool for estimating the microstructure of the weld deposit and the filler metal composition required to form ferrite in the deposit. This diagram (Figure 2) is used to predict the microstructure of stainless steel weld deposits on the basis of their chemical composition.

The Schaeffler diagram shows how the microstructure of the weld deposit is affected by those alloying elements in the stainless steel that act like nickel and those that act like chromium. The nickel equivalent group includes nickel, carbon, and manganese with an allowance being made for the nitrogen content of standard welds. The nickel equivalent is the ordinate of the diagram. The chromium equivalent group is the abscissa and includes the effects of chromium, molybdenum, silicon and columbium.

To estimate the microstructure of a deposit, the nickel equivalent and the chromium equivalent are calculated from the composition, using the following formulas:

$$\text{Nickel equivalent} = \%Ni + 30 \times \%C + 0.5 \times \%Mn$$

$$\text{Chromium equivalent} = \%Cr + \%Mo + 1.5 \times \%Si + 0.5 \times \%Gb$$

The values obtained are marked off on the coordinates of the diagram and, in this way, a point is located on the diagram. The microstructure shown at that point is the one predicted for a deposit of that composition. For example, a Type 302 stainless steel containing 0.10%C, 1.00%Mn, 0.5%Si, 17.5%Cr and 8.5%Ni has a nickel equivalent of 12.0 and a chromium equivalent of 18.25. In the form of a weld deposit, its microstructure is shown by the closed circle on the diagram. The deposit just manages to be fully austenitic.

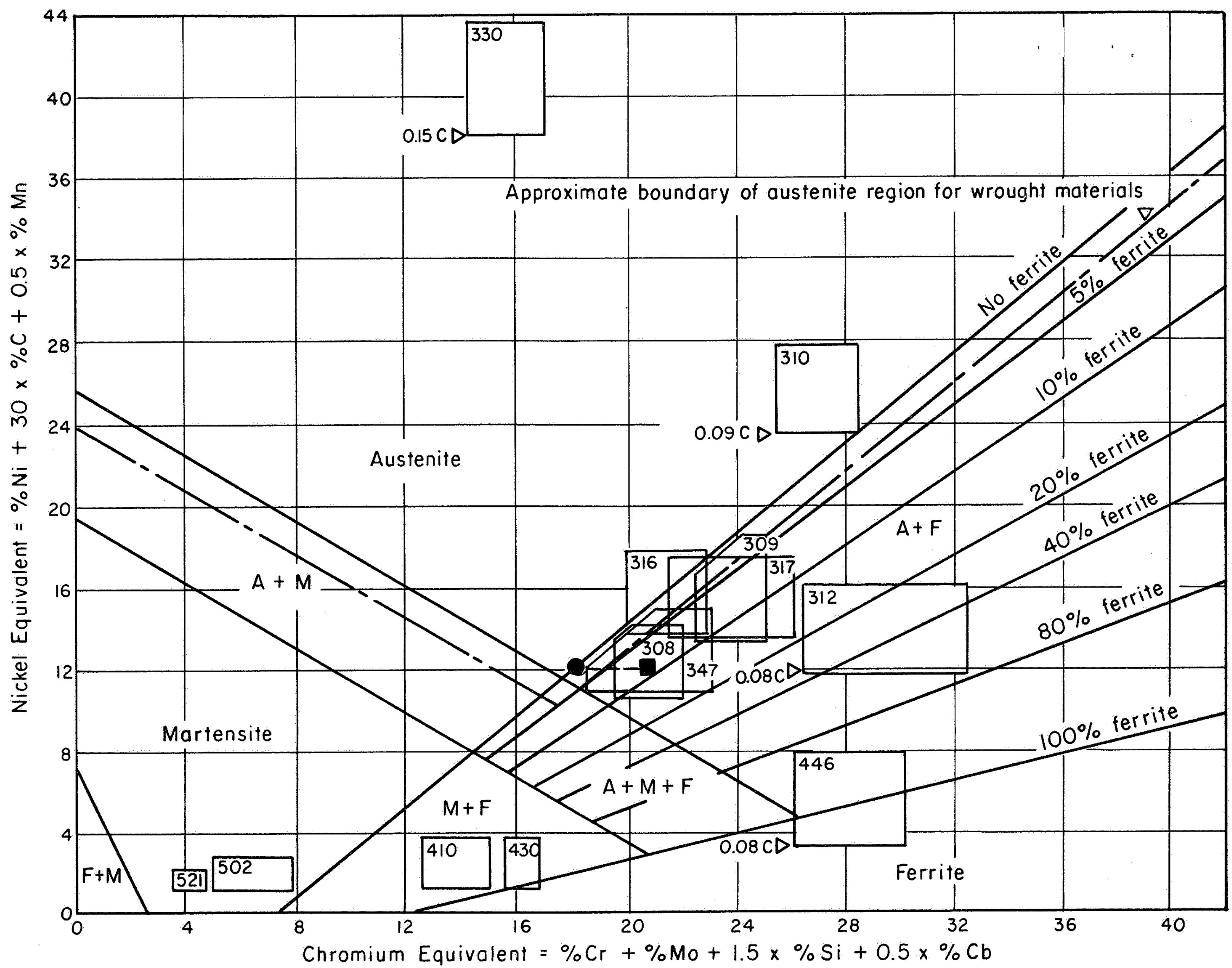


FIGURE 2. SCHAEFFLER'S DIAGRAM FOR THE MICROSTRUCTURE OF STAINLESS STEEL WELDS

To continue this example, this steel is welded with a Type 308 electrode having a composition and a structure represented by the closed square. A tie line connecting the square and the circle indicates the structures of the welds that would result from the combination, at all possible degrees of dilution. For instance, the diagram shows that, if the weld metal is diluted to the extent of 50 percent with parent metal in the course of the welding operation, the deposit will contain about 5 percent ferrite. Normally, such a deposit should have satisfactory resistance to hot cracking and it would not have impaired impact properties at very low temperatures.

The example just given can be turned around. The stainless steel to be welded will be represented by the closed circle, and it is desired to produce a weld metal containing an average of 5 percent ferrite. If the extent of dilution is 50 percent, the weld metal will have the proper composition if a Type 308 electrode is used that has the composition corresponding to the closed square.

Many factors influence the extent to which the weld metal is diluted by melted parent metal during the welding operation. Among them are the welding process, joint design, metal thickness, number of passes, current setting, and travel rate.

The Schaeffler diagram can also be used to predict electrode compositions required to avoid ferrite'or martensite in a stainless steel weld deposit. In addition, the diagram is helpful in estimating the trend of the microstructure developed when dissimilar steels are welded, An illustration of this situation is the welding of a stainless steel overlay on a piece of carbon steel chemical processing equipment. The carbon steel composition and the overlay composition are marked on the diagram, and the tie line drawn between them indicates the microstructures that may be encountered.

Carbide Precipitation. When austenitic chromium-nickel steels are welded, part of the heat-affected zone in the base metal and also part of the weld metal in multipass welds can become "sensitized". This sensitized area has a decreased resistance to corrosion by certain liquids and low notch toughness at low temperatures. This sensitization results from the precipitation of chromium carbides along the grain boundaries during welding (Ref. 10,11,15,16)

This intergranular chromium carbide formation promotes sensitivity in two ways. One way is by taking chromium, which is needed for corrosion resistance, away from the grains in the region of their boundaries. This is a direct result of the process of forming the carbides. The other way is by distributing a chemically different phase along the grain boundaries, that is, the chromium carbides themselves, which increases the possibilities for electrolytic or galvanic corrosion in these regions. In these ways, then, sensitization makes the grain boundary regions vulnerable and, thus, makes the metal susceptible to grain boundary or intergranular corrosion.

The part of the heat-affected zone in the parent metal which becomes sensitized is the region that is heated in the range of 800 to 1330 F during welding. This is the temperature range where chromium carbides precipitate from solid solution in austenitic stainless steels. Early passes of a multipass weld also can become sensitizied since they will also be heated into this temperature range or may stay in this temperature range during cooling for an extended length of time as subsequent passes are deposited.

Chromium carbides do not precipitate in that part of the weld joint which has not reached temperatures above 800 F during welding. Any chromium carbides observed in this region were present in the metal before welding and were due to other causes.

Near the fusion line, there is a region of the heat-affected zone where the temperature, during welding, ranges from 1300 F to the melting point of the base metal. This region is generally free of chromium carbides because they remain in solid solution at these temperatures. Moreover, the cooling rates are usually too fast for chromium carbides to precipitate during the cooling period after the welding has been completed.

Sensitization can be revealed by etching or pickling. For example, etching in a mixture of 10 percent nitric and 3 percent hydrofluoric acids shows the sensitized region as a severely attacked zone located a fraction of an inch from the weld bead. When polished and etched sections are examined with the microscope, the sensitized region of the weld-heat-affected zone is easily identified. It is the part of the metallographic specimen most readily attached by the etching media, and is distinguished by broadened and darkened grain boundaries. The severity with which the etchant attacks the grain boundaries in this region demonstrates how drastically its corrosion resistance has been reduced.

In most ordinary atmospheres, the performance of the steel is usually unaffected even though it contains regions that have been sensitized to some extent during welding. This also holds true for such mildly corrosive applications as dairy machinery, kitchen and restaurant equipment, and architectural items. However, in contact with strongly corrosive liquids, such as acid saline solutions, the sensitized regions may be corroded away at unacceptably high rates.

There are a number of ways by which the problem of sensitization can be reduced or eliminate. Some control can be exercised through the welding procedure. Other methods include reducing the carbon content of the steel, encouraging other carbides to form in preference to chromium carbides, and redissolving the chromium carbides by an annealing treatment after welding.

Welding Procedure. Steps to reduce the time the metal is held in the chromium carbide precipitation-temperature range of 800 to 1300 F during welding will reduce the severity of sensitization. The shorter the dwell time in this temperature range, the less intense will be the carbide precipitation and the less will be the degree of sensitization. These steps include welding rapidly, using small electrodes with minimum current settings, and using chill blocks.

Carbon Content. Using an extra low carbon, or "L", grade of austenitic chromium-nickel stainless steel is an especially effective way to approach the problem of sensitization.

Ideally, the carbon content should be below the solubility limit prevailing at the lowest temperature where the rate of chromium-carbide precipitation is significant. This temperature is about 800 F and the corresponding carbon content is in the order of 0.02 percent. Consistent achievmenet of so low a carbon content in commercial production is difficult. It is more practical to set a limit of 0.03 percent, as is done with the "L" grades. At this level of carbon content, the time for carbide precipitation to take place lengthens greatly and the amount that develops during welding is so small that little or no sensitization occurs as a result of normal welding and stress-relieving operations.

The thickness of the metal also influences carbide precipitation. Generally, thin sections cool through the chromium-carbide precipitation-temperature range faster than thick sections. Thus, less chromium carbides precipitate and the intensity of sensitization is less. Taking the effect of carbon and of section thickness together, it is clear that the thinner the gage the more carbon can be tolerated in the steel. For example, where Type 302 becomes too severely sensitized for the intended use, Type 304 can be substituted when the material is thin. On the other hand, for thick sections and extremely corrosive environments, the extra low-carbon Type 304L is preferred.

Stabilization. Another approach is to use Type 321 stainless steel to which titanium has been added or Type 347 stainless steel which contains columbium. These elements stabilize the microstructure by inducing the carbon in the steel to form carbides with them in preference to forming carbides with the chromium. The result is that the chromium in the steel is allowed to remain in the austenitic solid solution, where it can provide maximum corrosion protection. For low-temperature applications, however, the stabilized grades of stainless steel have the disadvantage of inherently low notch toughness at the service temperature (cryogenic temperatures).

The stabilized types of austenitic stainless steel are especially useful for equipment operating for long periods of time in the temperature range of 800 to 1600 F. Here, advantage can be taken of their superior high-temperature strength as well as their resistance toward sensitization. For room-temperature applications, an "L" grade is preferred largely because it is easier to weld.

Annealing. Sensitized austenitic stainless steel can be restored to its normal corrosion resistance by full annealing followed by rapid cooling. The precipitated chromium carbides are redissolved in the austenite by this heat treatment. However, the rapid cooling which is required imposes limitations on the usefulness of annealing. Only simple regularly shaped articles can be rapidly cooled from high temperatures without experiencing distortion. Hence, if distortion control is important and the component is irregular in shape and varies in thickness, annealing is not recommended.

Ferritic (Non-Hardenable) Chromium Stainless Steels. The ferritic stainless *steels are prone to weld-joint embrittlement. The notch sensitivity of these welds means that special care must be taken to avoid stress raisers such as sharp . notches, weld undercut and sharp surface irregularities.

Type 430 is probably the most widely used ferritic chromium stainless steel. As mill processed, the microstructure of this steel, which contains 16 to 18 percent chromium, consists of ferrite containing dispersed particles of chromium carbide.

However, when Type 430 is welded, changes take place in the microstructure of that part of the parent-metal heat-affected zone which reaches temperatures of 1600 F and above during welding. The iron-chromium-carbon constitution diagram shows that this steel becomes partly austenitic and partly ferritic at these temperatures. The proportions of austenite and ferrite in the microstructure at these temperatures depend on the composition of the particular heat of steel. However, the amount of austenite present is seldom more than 20 percent. On cooling to room temperature, this austenite transforms to a martensite of moderate hardness. The martensite generally occurs along the grain boundaries.

The microstructure of the higher chromium steels, such as Type 442 which contains 18 to 23 percent chromium and Type 446 with 23 to 27 percent chromium, generally remains entirely ferritic during welding. Likewise, chromium stainless steels containing aluminum such as Type 405, or titanium such as Type 430Ti, remain ferritic.

The grain growth which occurs in the heat-affected zone reduces the toughness and ductility of the weldment to a slight extent, Considerable grain growth is characteristic of ferritic stainless steels heated to extremely high temperatures. Grain refinement does not take place in these steels through heat treatment alone. To reduce the grain size requires cold working followed by annealing.

The martensite that forms along the grain boundaries in the heat-affected zones of welds made in Type *430* stainless steel tends to exert a somewhat embrittling-effect. Annealing at 1350 to 1500 F restores the steel to the completely ferritic condition and removes brittleness caused by the presence of martensite.

Martensitic (Hardenable) Chromium Stainless Steels. The martensitic stainless steels when heated and cooled undergo metallurgical changes similar to low-alloy steels. At room temperature, they normally are ferritic. The micro-structure changes to austenite when the steel is heated above about 1800 F. Upon fast cooling from this temperature, the austenite transforms to hard martensite. (Slow cooling results in soft ferrite.) Cooling in air normally is fast enough to cause the martensite transformation. This means that when these steels are welded, the joint becomes hard and brittle after cooling.

The raw martensite formed on cooling the martensitic stainless steels from elevated temperatures tends to be brittle. Therefore, these steels are annealed, stress relieved, or tempered before being placed in service.

In addition, these steels tend to experience considerable grain growth in the highly heated parent metal next to the weld. Refinement of the grains in this region can be accomplished by giving the metal a standard annealing treatment after welding.

The standard annealing practice is to heat to about 1600 F, slow cool to about 1100 F, and then air cool to room temperature. Stress relieving is done at 1200 to 1400 F, followed by slow cooling to 1100 F and then air cooling to room temperature. The reason for the air cooling step is to pass quickly through the temperature range of 800 to 900 F where brittleness may develop. Tempering is usually carried out at temperatures of 950 F and above, the embrittling temperature range again being avoided.

Actually, the martensite transformation in the hardenable chromium stainless steels depends on the carbon content as well as on the chromium content. Not only must the chromium content be limited, but the carbon content must be above a minimum if a fully martensitic structure is to develop. For example, Type 410 requires more than 0.08 percent carbon to be completely martensitic. Those 13 percent chromium steels which contain less than 0.08 percent carbon, such as the so-called modified or low-carbon versions of 410, are partially ferritic and behave very much like Type 430.

Again, like other martensitic steels, the strength hardness and tendency toward cracking of the hardenable chromium stainless types increase as the carbon content is increased. Below 0.10 percent carbon, the tendency of a weldment in these steels to crack is not great and welding can usually be done without preheat or postheat. At carbon contents of 0.10 to 0.20 percent, preheating at about 500 F and the use of a 500 F interpass temperature are strongly recommended to avoid cracking. When the carbon content is above 0.20 percent, not only should the work be preheated but also it should be annealed or otherwise heat treated immediately after welding.

FILLER MATERIALS

Standardized compositions for stainless steel welding rod, bare wire, and covered electrodes are covered by American Welding Society specifications. These compositions (along with several nonstandard compositions) are listed in Tables I and II. Generally, filler metals are selected that deposit a weld metal with a composition similar to that of the base metal so that corrosion resistance and mechanical properties match (Ref. 16). However, the correct filler metal does not always match the base metal. The filler metals commonly used with the various grades of stainless steel are listed in Table III. Filler metals for welding various combinations of stainless steels are listed in Table IV.

TABLE I. COMPOSITIONS OF WELD METALS DEPOSITED BY STAINLESS STEEL COVERED ELECTRODES

Note 1. Analysis shall be made for the elements for which specific values are shown in the table. If, however, the presence of other elements is indicated in the course of routine analysis, further analysis shall be made to determine that the total of these other elements, except iron, is not present in excess of 0.70 percent.

Note 2. Single values shown are maximum percent g s exc pt whe e therwi e spe fi a

AWS-ASTM Classification	Carbon,[a] percent	Chromium, percent	Nickel, percent	Molybdenum, percent	Columbium Plus Tantalum, percent	Manganese, percent	Silicon, percent	Phosphorus, percent	Sulfur, percent	Tungsten, percent	Ref
E308	0.08	18.0 to 21.0	9.0 to 11.0	---	---	2.5	0.90	[illegible]		---	19
E308L	0.04	18.0 to 21.0	9.0 to 11.0	---	---	2.5	0.90	0.04	0.03	---	"
E309	0.15	22.0 to 25.0	12.0 to 14.0	---	---	2.5	0.90	0.04	0.03	---	"
E309Cb	0.12	22.0 to 25.0	12.0 to 14.0	---	0.70 to 1.00	2.5	0.90	0.04	0.03	---	"
E309Mo	0.12	22.0 to 25.0	12.0 to 14.0	2.0 to 3.0	---	2.5	0.90	0.04	0.03	---	"
E310	0.20	25.0 to 28.0	20.0 to 22.5	---	---	2.5	0.75	0.03	0.03	---	"
E310Cb	0.12	25.0 to 28.0	20.0 to 22.0	---	0.70 to 1.00	2.5	0.75	0.03	0.03	---	"
E310Mo	0.12	25.0 to 28.0	20.0 to 22.0	2.0 to 3.0	---	2.5	0.75	0.03	0.03	---	"
E312	0.15	28.0 to 32.0	8.0 to 10.5	---	---	2.5	0.90	0.04	0.03	---	"
E16-8-2	0.10	14.5 to 16.5	7.5 to 9.5	1.0 to 2.0	---	2.5	0.50	0.03	0.03	---	"
E316	0.08	17.0 to 20.0	11.0 to 14.0	2.0 to 2.5	---	2.5	0.90	0.04	0.03	---	"
E316L	0.04	17.0 to 20.0	11.0 to 14.0	2.0 to 2.5	---	2.5	0.90	0.04	0.03	---	"
E317	0.08	18.0 to 21.0	12.0 to 14.0	3.0 to 4.0	---	2.5	0.90	0.04	0.03	---	"
E318	0.08	17.0 to 20.0	11.0 to 14.0	2.0 to 2.5	6 x C, min to 1.00 max	2.5	0.90	0.04	0.03	---	"
E330	0.25	14.0 to 17.0	33.0 to 37.0	---	---	2.5	0.90	0.04	0.03	---	"
E347[b]	0.08	18.0 to 21.0[d]	9.0 to 11.0	---	8 x C, min[e] to 1.00 max	2.5	0.90	0.04	0.03	---	"
E349	0.13	18.0 to 21.0	8.0 to 10.0	0.35 to 0.65	0.75 to 1.2	2.5	0.90	0.04	0.03	1.25 to 1.75	"
E410	0.12	11.0 to 13.5	0.60	---	---	1.0	0.90	0.04	0.03	---	"
E430	0.10	15.0 to 18.0	0.60	---	---	1.0	0.90	0.04	0.03	---	"
431[e]	0.06	16.25	2.10	---	---	0.50	0.40	---	---	---	20
442[e]	0.08	18.50	0.40	---	---	0.60	0.40	---	---	---	20
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	---	---	---	20

a. Carbon shall be analyzed to the nearest 0.01 percent.
b. Chromium shall be 1.9 x Ni, min, when so specified.
c. Tantalum shall be 0.10 max, when so specified.
d. Titanium shall be 0.15 max.
e. These electrodes are not covered by AWS standards.

TABLE II. COMPOSITIONS OF BARE FILLER WIRES FOR WELDING STAINLESS STEELS

Note 1. Analysis shall be made for the elements for which specific values are shown in this table. If, however, the presence of other elements is indicated in the course of routine analysis, further analysis shall be made to determine the total of these other elements, except iron, is not present in excess of 0.70 percent.

Note 2. Single values shown are maximum percentages except where otherwise specified.

AWS-ASTM Classification	Carbon, percent	Chromium, percent	Nickel, percent	Molybdenum, percent	Columbium Plus Tantalum, percent	Manganese percent	Silicon, percent	Phosphorus, percent	Sulfur, percent	Tungsten, percent	Ref
ER308[a]	0.08	19.5 to 22.0	9.0 to 11.0	---	---	1.0 to 2.5	0.25 to 0.60	0.03	0.03	---	21
ER308L[a]	0.03	19.5 to 22.0	9.0 to 11.0	---	---	1.0 to 2.5	0.25 to 0.60	0.03	0.03	---	"
ER309	0.12	23.0 to 25.0	12.0 to 14.0	---	---	1.0 to 2.5	0.25 to 0.60	0.03	0.03	---	"
ER310	0.08 to 0.15	25.0 to 28.0	20.0 to 22.5	---	---	1.0 to 2.5	0.25 to 0.60	0.03	0.03	---	"
ER312	0.08 to 0.15	28.0 to 32.0	8.0 to 10.5	---	---	1.0 to 2.5	0.25 to 0.60	0.03	0.03	---	"
ER316	0.08	18.0 to 20.0	11.0 to 14.0	2.0 to 3.0	---	1.0 to 2.5	0.25 to 0.60	0.03	0.03	---	"
ER316L	0.03	18.0 to 20.0	11.0 to 14.0	2.0 to 3.0	---	1.0 to 2.5	0.25 to 0.60	0.03	0.03	---	"
ER317	0.08	18.5 to 20.5	13.0 to 15.0	3.0 to 4.0	---	1.0 to 2.5	0.25 to 0.60	0.03	0.03	---	"
ER318	0.08	18.0 to 20.0	11.0 to 14.0	2.0 to 3.0	8 x C, min to 1.0 max	1.0 to 2.5	0.25 to 0.60	0.03	0.03	---	"
ER321[c]	0.08	18.[illegible] to 20.5	9.0 to 10.5	0.5 max	---	1.0 to 2.5	0.25 to 0.60	0.03	0.03	---	"
ER347[a]	0.08	19.0 to 21.5	9.0 to 11.0	---	10 x C, min to 1.0 max	1.0 to 2.5	0.25 to 0.60	0.03	0.03	---	"
ER348[a]	0.08	19.0 to 21.5	9.0 to 11.0	---	10 x C, min to 1.0 max[b]	1.0 to 2.5	0.25 to 0.60	0.03	0.03	---	"
ER349[d]	0.07 to 0.13	19.0 to 21.5	8.0 to 9.5	0.35 to 0.65	1.0 to 1.4	1.0 to 2.5	0.25 to 0.60	0.03	0.03	1.25 to 1.75	"
ER410	0.12	11.5 to 13.5	0.6	0.6	---	0.6	0.50	0.03	0.03	---	"
ER420	0.25 to 0.40	12.0 to 14.0	0.6	---	---	0.6	0.50	0.03	0.03	---	"
ER430	0.10	15.5 to 17.0	0.6	---	---	0.6	0.50	0.03	0.03	---	"
442[e]	0.09	18.5	---	0.2	---	0.50	0.35	---	---	---	20
446[e]	0.10	28.0	---	---	---	0.70	0.40	---	---	---	20

a. Chromium, min = 1.9 x Nickel, when specified

b. Tantalum, max = 0.10 percent.

c. Titanium = 9 x C, min to 1.0, max.

d. Titanium = 0.10 to 0.30.

e. These wires are not covered by AWS standard

TABLE III. FILLER METALS USED TO WELD VARIOUS GRADES OF STAINLESS STEEL (REF. 10, 11, 15)

Base metal: Wrought	Base metal: Cast(1)	Service condition of base metal	Covered electrode	Bare rod or filler wire
201, 202, 301, 302, 304, 305, 308	CF-8, CF-20	As welded or annealed	E308	ER308
302B		As welded	E309	ER309
303, 303Se		As welded or annealed	E312	ER314
304L	CF-3	As welded	E308L, E347	ER308L, ER347
308L		As welded	E308L	ER308L
309	CH20	As welded	E309	ER309
309S			E309, E309Cb	ER309
310	CK-20	As welded	E310	ER310
310S		As welded	E310, E310Cb	ER310
316	CF-8M, CF-12M	As welded or annealed	E316, E309Cb(2)	ER316(3)
316L	CF-3M	As welded or stress relieved	E316L, E309Cb(2)	ER316L(3)
317	CG-8M	As welded or annealed	E317(2)	ER317
321, 321H		As welded	E347	ER321, ER347
347, 347H, 348, 348B		As welded	E347	ER347
403, 410		Annealed or hardened	E410	ER410
		As welded	E308, E309, E310	ER308, ER309, ER310
405		Annealed	E430	ER430
420		Annealed or hardened	E420	ER420
		As welded	E308, E309, E310	ER308, ER309, ER310
430		Annealed	E430	ER430
		As welded	E308, E309, E310	ER308, ER309, ER310
430Ti		As welded	E430	430Ti(4), ER 430
431		Annealed or hardened	431(4)	431(4)
		As welded	E308, E309, E310	ER308, ER309, ER310

TABLE III. Continued

Base metal		Service condition of base metal	Covered electrode	Bare rod or filler wire
Wrought	Cast[1]			
42		Annealed	442[4]	442[4]
		As welded	E308, E309, E310	ER308, ER309, ER310
46		Annealed	446[4]	446[4]
		As welded	E308, E309, E310	ER308, ER309, ER310

1) Castings higher in carbon but otherwise of generally corresponding composition are available and are designated by the prefix "H" (see Table VII). Filler metals for these alloys are high carbon versions of the listed filler metals if available.

2) Joints deposited by 316, 316L, 317 electrodes and filler wires may occasionally display poor corrosion resistance in the as-welded condition particularly in hot acids. The use of 309 or 309Cb filler metals often provides a more suitable weld metal. Corrosion resistance of the molybdenum-bearing stainless steels can be restored by heat treating:

(1) For Types 316 and 317 - full anneal at 1950-2050 F
(2) For Types 316L and 317L - stress relieve at 1600 F

3) Same comments as Footnote 2. However, 309Cb bare wire is not regularly available. ER310 is the best substitute.

4) No standard AWS designation although this filler wire or electrode is available commercially.

TABLE IV. GENERAL GUIDE FOR SELECTING ELECTRODES AND WELDING RODS FOR DISSIMILAR METAL JOINTS IN AUSTENITIC STAINLESS STEEL (REF. 11)

AISI Type	304L	308	309	309S	310	310S	316 316H	316L	317	321 321H	347,347H 348,348H
304H,305,304	308	308	308 309	308 309	308 309 310	308 309 310	308 316	308 316	308 316 317	308	308
304L		308	308 309	308 309	308 309 310	308 309 310	308 316	308L 316L	308 316 317	308L 347	3081 347
308			308 309	308 309	308 309 310	308 309 310	308 316	308 316	308 316 317	308	308 347
309				309	309 310	309 310	309 316	309 316	309 316	309 347	309 347
309S					309 310	309S 310S	309 316	309S 316L	309 316	309 347	309 347
310							316 310 310Mo	316 310Mo 310	317 310Mo 310	308 310	308 310
310S							316 310Mo	316 310Mo	317 310Mo	308 310	308 310
316H,316								316	317 316	308 316	308 316 347
316L									317	316L	3161 347
317										308 317	308 317 347
321H,321											3081 347

*Electrodes and welding rods listed are not in any preferred order.

MATERIAL CONDITION FOR WELDING

It is necessary to be sure that corrosion and oxidation resistance of these lloys are not lowered during fabrication operations. Corrosion resistance can e seriously affected by contamination during joining or heat-treating operations f either base metal or weld metal by dirt, oils, grease, crayon marks, etc. on he surface (Ref. 15). Carbon pickup from surface contaminants can adversely ffect corrosion resistance. Sulfur pickup can affect both corrosion resistance nd properties and cause cracking (Ref. 17, 18). Other materials,e.g. zinc, brass can affect arious properties adversely. Consequently, the surfaces of all parts must be lean before joining or heat treatment is undertaken.

Dirt and films of oil and grease can be removed by washing or by degreasing perations. Soaps can be removed with hot water. Removal of soluble oils, tallow id fats require a hot alkaline solution wash followed by a hot water rinse.

Scale and oxide films can be removed from stainless steel by grinding, filing, r wire brushing. Hot-cut edges of weld joints should be machined or ground down o bright metal. Brushes and other cleaning tools should be made of stainless teel instead of carbon steel to avoid picking up bits of carbon steel in the ork and contaminating the weld metal. Tools used to clean stainless steel hould not be used to clean other metals. If they are, grease, dirt, or bits of ther metals can be carried to the stainless steel.

Oxide films and scale also can be removed by pickling. Typical pickling equences, solutions and times are given in Tables V and VI.

If the parts are exposed to the atmosphere after cleaning, they may become econtaminated. Dust, oil, grease, dirt and similar contaminants are present n most shop atmospheres. Joint areas may be cleaned of this type of contamination y wiping with lint-free cloths dampened with a solvent such as methyl-ethyl ketone. owever, it may be advisable to prevent recontamination after cleaning. This can

TABLE V. TYPICAL SEQUENCE OF PROCEDURES FOR PICKLING SERIES 300 STAINLESS STEELS (REF. 22)

Cycle	Solution: Composition, % by volume(a)	Solution: Operating temperature, F	Immersion time, min(b)
1. Sulfuric acid dip	15 to 25 H_2SO_4(c)	160 to 180	30 to 60
2. Water rinse(d)	---	Ambient	---
3. Nitric-hydrofluoric acid dip	5 to 12 HNO_3; 2 to 4 HF	120 max	2 to 20
4. Water rinse(d)	---	Ambient	---
5. Caustic-permanganate dip (e)	18 to 20 NaOH; 4 to 6 $KMnO_4$(f)	160 to 200	15 to 60
6. Water rinse(d)	---	Ambient	---
7. Sulfuric acid dip	15 to 25 H_2SO_4(c)	160 to 180	2 to 5
8. Water rinse(d)	---	Ambient	---
9. Nitric acid dip	10 to 30 HNO_3	120 to 180	5 to 15
10. Water rinse (dip)	---	Ambient(g)	---

(a) Acid solutions are not inhibited. (b) Shorter times are for lower-alloy steels; longer times are for more highly alloyed types, such as 309, 310, 316, 317 and 318. (c) Sodium chloride (up to 5% by weight) may be added. (d) Dip or pressure spray. (e) Sometimes used to loosen scale. (f) Percent by weight. (g) Boiling water may be used to facilitate drying.

TABLE VI. TYPICAL SEQUENCE FOR PICKLING LOW-CARBON SERIES 400 STAINLESS STEELS (REP. 22)

Cycle	Solution: Composition % by volume(a)	Solution: Operating temperature, F	Immersion time, min(b)
1. Sulfuric acid dip	15 to 25 H_2SO_4(b)	160 to 180	5 to 30
2. Water rinse(c)	---	Ambient	---
3. Caustic permanganate dip(d)	18 to 20 NaOH; 4 to 6 $KMnO_4$(e)	160 to 200	20 min to 8 hr(f)
4. Water rinse(c)	---	Ambient	---
5. Sulfuric acid dip	15 to 25 H_2SO_4(b)	160 to 180	2 to 3
6. Nitric acid dip	30 HNO_3	Ambient	10 to 30
7. Water rinse (dip)	---	Ambient (g)	---

(a) Acid solutions are not inhibited, (b) Sodium chloride (up to 5% by weight) may be added. (c) Dip, pressure hose, or spray. High-pressure spray or jets are more effective for removing scale and smut. (d) Sometimes used to loosen scale. (e) Percent by weight. (f) Immersion time may exceed this range. (g) Boiling water may be used to facilitate drying.

be done by using the cleaned materials within a short time after cleaning. If "this cannot be done they can be protected by covering with lint-free and oil-free wrappings,

The effectiveness of a cleaning operation can be evaluated by various methods. Contact resistance measurements can be used although this technique is not widely used. A common method of evaluating the effectiveness of descaling and pickling operations is to observe water breaks during the rinsing operation. If the cleaned surface is uniformly wet by the water the surface is considered clean. If the water collects in drops or patches it is said to "break". The presence of a water break indicates that the surface has not been well cleaned.

More detailed descriptions of metal cleaning process and techniques can be found in the literature (Ref. 22).

JOINT PREPARATION

The method of joint preparation for stainless steels can be any one of the following: machining (all types), shearing, grinding, flame cutting (iron powder or flux) and plasma cutting. The applicable machining, shearing and grinding techniques are those used for most stainless steel shaping and will not be covered here. Flame-cutting techniques which utilize either iron oxide or special fluxes in the cutting flame to melt or react with the chromium oxide that is formed have been developed for cutting the stainless steels. These, however, are being largely replaced by plasma-arc cutting. The plasma arc provides the necessary heat to melt the chromium oxide which is the main hindrance to normal flame cutting of the stainless steels. The high-speed gas (plasma) stream also blows the molten metal away from the cutting face. The plasma arc can be used to cut any material that is electrically conductive. Therefore, this method is commonly used to cut metals that are difficult or impossible to cut efficiently by conventional metal-cutting methods such as the oxyacetylene cutting process.

Plasma-Arc Cutting. For cutting metals, the plasma arc is established between the electrode and the workpiece; various gases are used to form the plasma, depending on the particular metal being cut. In contrast to the oxy-acetylene process, where the cutting speed is limited by the rate at which the chemical reaction between oxygen and iron proceeds, the cutting speed of the plasma arc is limited only by the power available for cutting and the quality of the cut itself. The quality of cutting is governed largely by the choice and/or magnitude of the following process variables: (1) type of plasma gas, (2) gas flow rate, (3) cutting speed, and (4) stand-off distances. Torch parameters such as the size of the cutting tip and the selected power level are more in the nature of dependent variables. Once they are selected, the process variables can be adjusted to produce acceptable cutting. Care must be exercised in making such adjustments when optimum cutting conditions are required, since minor variations affect the smoothness of the cut surface, the amount of dross adhering to the cut, and the production of an undesirable beveled surface.

Typical conditions for plasma cutting of stainless steels are given in Table VII.

DISTORTION CONTROL AND TOOLING

Because of the pattern of heating and cooling which develops during welding, any welded part is subject to a certain amount of distortion. The amount of distortion occurring in welded stainless steels may be greater than that encountered with other materials, particularly low-alloy steels. This is because the stainless

TABLE VII. PLASMA-ARC CUTTING CONDITIONS FOR TYPE 304 STAINLESS STEELS (REF. 23)

Thickness, in.	Tip Diameter, in.	Plasma Gas Flow Rate, cfh N_2	H_2	A	Power, kw	Cutting Speed. ipm
1/4	3/32	90	5	---	30	35
1/2	3/32	90	5	---	30	25
1	7/64	120	10	---	50	30
1	9/64	150	20	---	100	55
1	1/8	---	20	145	30	25
1-1/2	9/64	150	20	---	100	30
1-1/2	1/8	---	20	145	50	20
2	9/64	150	20	---	100	15
2	7/32	---	60	110	100	30
3	3/16	200	20	---	150	10
3	7/32	---	60	110	100	25
4	3/16	200	20	---	200	6
4	7/32	---	60	110	100	25
5	7/32	---	70	130	150	10
6	7/32	---	70	130	150	6
8	7/32	---	70	130	150	4

Note: For a given plate thickness there is more than one set of conditions that will produce acceptable cuts.

steels expand more on heating and do not conduct the heat of the arc away from the weld area nearly as fast as do low-alloy steel and other metals. For these reasons, greater care is required to control distortion in stainless steel than is required for other metals,

A butt weld in stainless steel sheet will become bowed in the direction of the weld. This is due to the lengthwise shrinkage of the weld metal and is called the "drawstring effect". The weld also shrinks across its width and, in so doing, will cause the two pieces being welded to draw together and close up the joint ahead of the weld. Surprisingly, plates and sheets may spread apart if the welding travel speed is high enough. Welds in plate do not bow appreciably because the restraint is so high. However, they are subject to angular distortion. This type of distortion occurs in plate when a beveled joint and a number of passes are used. The opening at the top of the joint is considerably wider than at the bottom of the joint. Moreover, the root pass acts as a pivot, keeping the parts from pulling in uniformly across the joint width. Then, as each pass after the root pass is put in and shrinks, it will pull the two pieces together at an angle. Fillet, lap, and corner welds also are subject to similar distortions.

There are three basic methods of controlling distortion caused by welding: (1) reduce shrinkage forces by controlling weld-bead sequence and heat input, (2) offset the parts, and (3) restrain the joint by tacking and by using jigs and fixtures.

DISTORTION CONTROL BY REDUCTION OF SHRINKAGE FORCES

Shrinkage forces cannot be eliminated. However, there are methods for reducing the distortion caused by shrinkage forces. These methods include avoiding overwelding, being sure of good fitup, using backstep and skip welding, and controlling heat input and preheat.

Excess weld metal may increase distortion because there is more metal to shrink. Ideally, the surface of a butt weld should be flush with the surface of the base metal. This is difficult to do, so butt welds are made with a small amount of reinforcement. However, the amount of reinforcement should be kept as small as possible. For a fillet or lap weld, the strength of the joint is determined by the throat depth of the weld. Excess weld metal does not increase the strength here, for once the fillet is large enough the base metal becomes the weakest link in the chain. The size of lap and fillet welds should not exceed the size indicated in specifications or on drawings. The surface of these welds should be as flat as the welder can make them.

One way to avoid excess weld metal and, thus, reduce distortion is to use correct joint spacing (gap or root opening). Use a joint opening wide enough for good penetration, but no wider. If the opening is too wide, more weld metal will be needed to fill the gap and more shrinkage will occur. Correct joint gap usually is no more than 1/16 inch regardless of the welding process or thickness. No gap is possible with many processes and thin materials.

Backstep and skip welding can be used for long continuous welds. In both of these methods, short intermittent welds are made. For backstep welding, each bead is started some distance ahead of the previous bead and is welded back to join the beginning of the previous bead. A skip weld is a series of short beads made some distance apart, The gaps between the beads are welded in after the beads have cooled. These techniques usually are used with shielded metal-arc welding or with manual GMA welding.

When welding thin material, lengthwise or "drawstring" bowing of the part is usually the most serious type of distortion. This can be reduced by using as small an electrode size (shielded metal-arc and GMA welding) and as low a current setting as is practical. In thicker material, crosswise or angular distortion is more apt to occur. This can be reduced by cutting down the number of passes, making the passes heavier, and increasing the welding travel speed.

DISTORTION CONTROL BY OFFSETTING PARTS AND BALANCING SHRINKAGE FORCES

If the operator can estimate the amount of shrinkage or distortion that will occur in a particular weld joint, he can correct for this distortion by offsetting the parts. The welding distortion then will pull the parts into the correct position or alignment.

This method is particularly good for T-joints. The "leg" of the T is offset before the weld is made. The shrinkage of the weld pulls the leg to its proper 90-degree position. If two welds are to be made, one on each side of the leg, the "cap" of the T could be bent slightly before the welding with the same results after the welds are complete. Butt welds and corner welds made from one side can be offset before welding to compensate for distortion. The amount of offset required will vary greatly, depending on the material thickness, welding parameters, welding process, and welding technique. No specific data are available for the amount of offset required for stainless steels.

Offsetting or prebending usually is used for short welds and simple shapes. For long welds, or for welds in complex structures, these methods may become too complicated to give satisfactory results.

Shrinkage forces can often be balanced against each other to prevent distortion. Double-V or U joints can be welded without angular distortion if the proper welding sequence is used. If the beads are deposited alternately on opposite sides of the joint, the shrinkage of one bead will be balanced against the shrinkage from the bead made on the other side of the joint and the parts should remain flat. The same results can be obtained in T-welds by making short intermittent welds on opposite sides of the leg.

DISTORTION CONTROL BY TACK WELDING AND JIGGING

Usually the most practical way to prevent distortion is to fasten or clamp the parts rigidly before welding so that they cannot move. For simple welds, this can be done by tacking before welding. For Large parts for complex shapes or for critical assemblies jigs or fixtures are needed.

Tackwelding. Tack welds are used chiefly to keep the parts from drawing together or spreading apart during welding. In other words, they are used to maintain the right joint alignment and gap. They will not prevent angular or lengthwise distortion or bowing. Tack welds should always be used when the parts are not clamped in a jig and sometimes they are useful even with a jig. The spacing between tack welds depends on the thickness of the material -- the thinner the material the closer the tack welds. They may be as close as 3/4 inch if necessary.

Tack welds, however, can be a source of defects when the subsequent welds are made. Tack welds are subject to cracking if they are too small. For this reason, they should always be inspected and, if cracked, ground out before subsequent welding. Sound tack welds should be ground to a smooth contour that blends evenly into the base metal. This will facilitate complete melting of the tack weld into the subsequent weld.

Jigging. Jigs are used for two purposes: (1) to hold the pieces during welding, and (2) to prevent distortion. For holding pieces together for welding, jigs can be used with any thickness of material. To control distortion, though, jigging is not very effective for material over about 1/4 inch thick. The shrinkage forces that develop in welds of thick material become so great that a jig to hold these forces would be too bulky to be practical. Thus, other means of controlling distortion should be used when welding thick stainless steel sections.

Jigs can be simple or complex, depending on the shape of the parts being welded. The complex jigs usually are intended for only one specific job run, Simple jigs, though, can be used for a wide variety of welding jobs.

The simplest jig consists of a backup bar, two hold-down bars, and some C-clamps (Figure 3). The backup bar should be grooved so that proper weld penetration can be obtained. This groove should be about 3/32 inch deep and about 10 times wider than the sheet thickness, but never less than 3/16 inch wide. Copper is the best material for the backup bar. The weld metal will not fuse to the copper and the copper will act as a chill bar to cool the weld joint quickly to aid in reduction of distortion. The hold-down bars may be of steel or copper with copper preferred if rapid cooling is desired. Water cooled jigs are sometimes used to confine the welding heat and promote fast cooling. The edges of the hold-down bars are beveled *so* that there is room to weld.

Both the hold-down and backup bars should be rigid *so* that the weld shrinkage will not bend the jig parts. The bars should be at least 1/2 inch thick. A good practice is to make the backup bar of steel with a grooved copper insert. Added rigidity can be obtained by using angles, T-sections, or T-beams for the hold-down and backup bars.

Where long welds are to be made, these simple jigging systems often become awkward to use. If the pieces being welded are also wide, it may be possible to apply clamps only at the ends of the joint. To clamp the center of the joint would require C-clamps with impractical throat depths. For such applications, special jigs have to be built or purchased commercially. One jigging method uses common fire hose as the clamping device. The fire hose is inflated with air under pressure to force the clamping fingers against the parts being welded

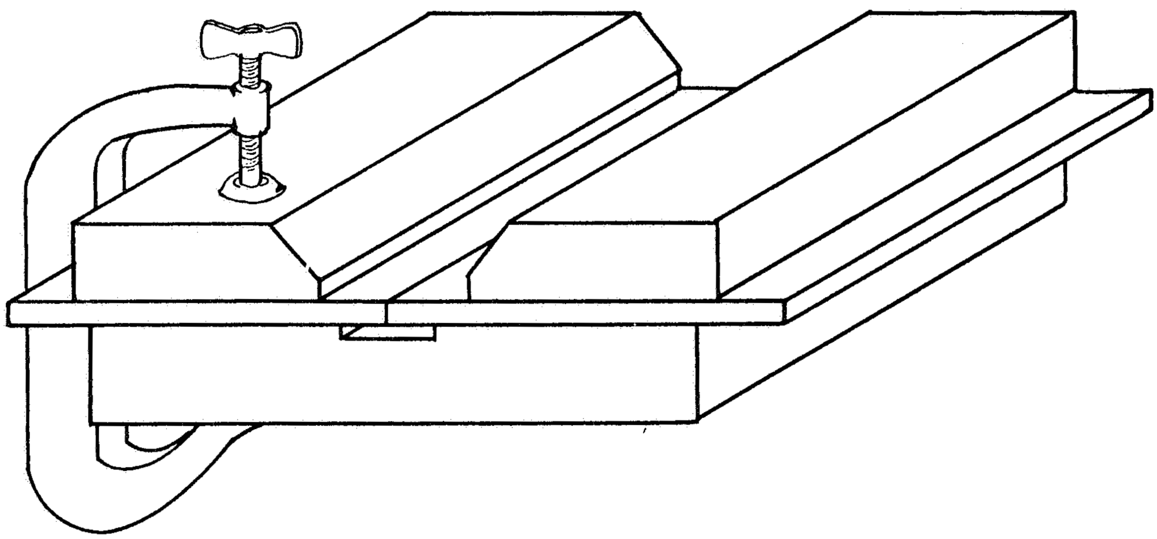


FIGURE 3. SIMPLE JIGGING FOR BUTT WELDS

(Figure 4). Other jigs use various types of mechanical fingers to apply the clamping pressure and are called stake welders or stake fixtures (Figure 5).

Fillet welds and corner welds can be jigged using the simple "angle-iron and C-clamp" equipment. The sharp corners on the angle pieces should be ground off so that good fitup can be obtained. As with butt welds, long fillet or corner joints will require special jigs. The examples given for butt welds can be modified easily for fillet and corner welds. The same jigging principles also apply to edge and lap welds. The jigging may also be combined with the welding mechanism where precise control of the orientation of the welding torch with the joint is required. Such a setup is illustrated in Figure 6. This apparatus was used for fabricating the stainless steel dome sections of Atlas and Centaur missile tankage. The pieces to be welded are clamped to the conical shaped jig. The GTA welding torch rides on the curved track. Both the track and jig are integral parts of the equipment assembly so their relative positions are rigidly maintained.

The tooling used in resistance welding stainless steels is generally similar to tooling used in resistance welding other materials. Resistance-welding tooling consists of suitable fixtures or jigs to hold the parts in proper position for welding and to conduct welding current to the parts. Sometimes tooling is also designed to index the part through the welding equipment to insure that welds are made at the proper positions. The same general rules followed in designing any resistance-welding tooling should be followed for tooling designed for use with stainless steels. Generally, this means that nonmetallic or nonmagnetic components should be used exclusively, and the tooling should not contaminate the base metal.

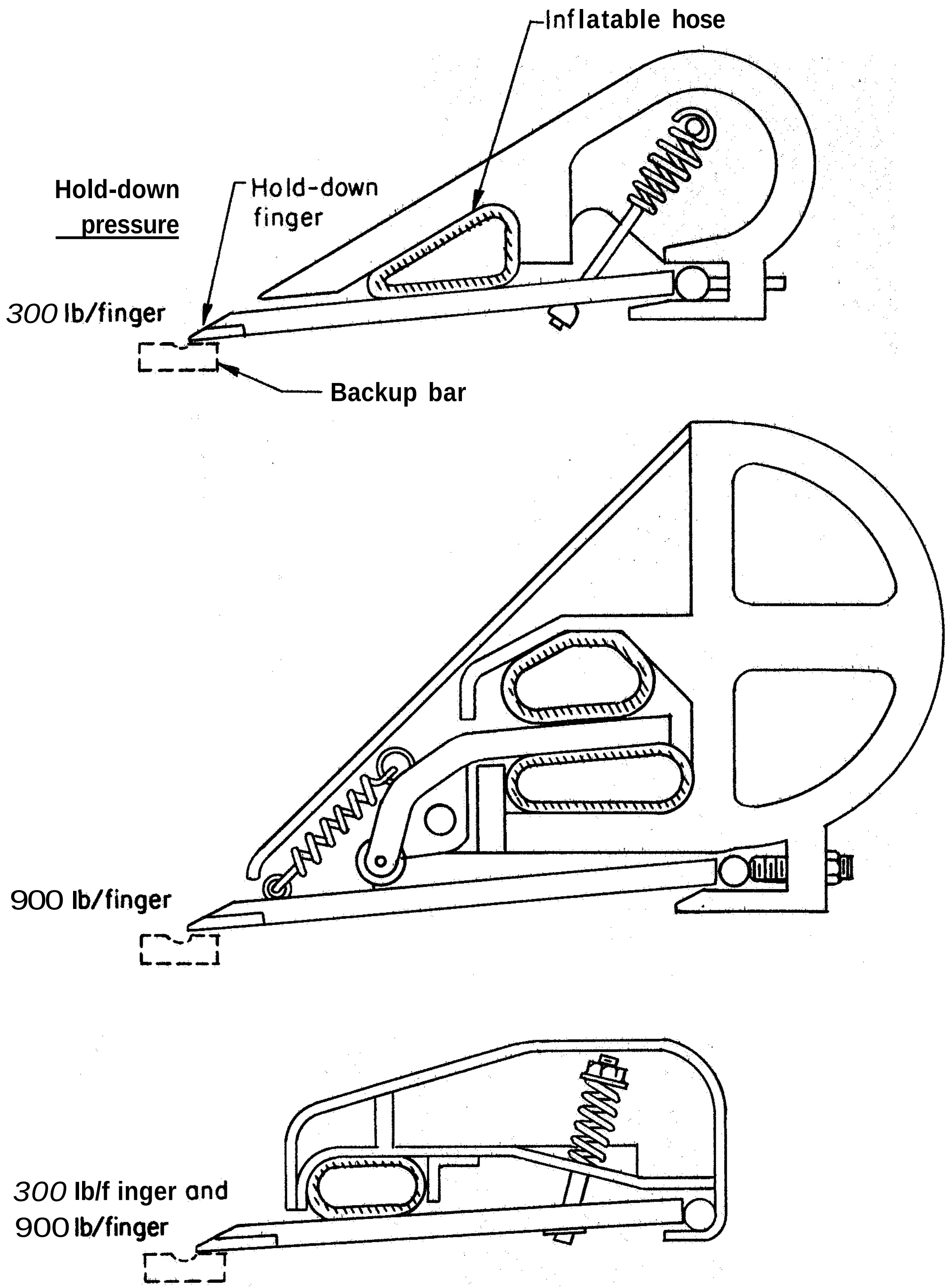


FIGURE 4, VARIOUS SYSTEMS FOR ACTUATING HOLD-DOWN FINGERS IN WELDING JIGS (Courtesy Airline Welding and Engineering)

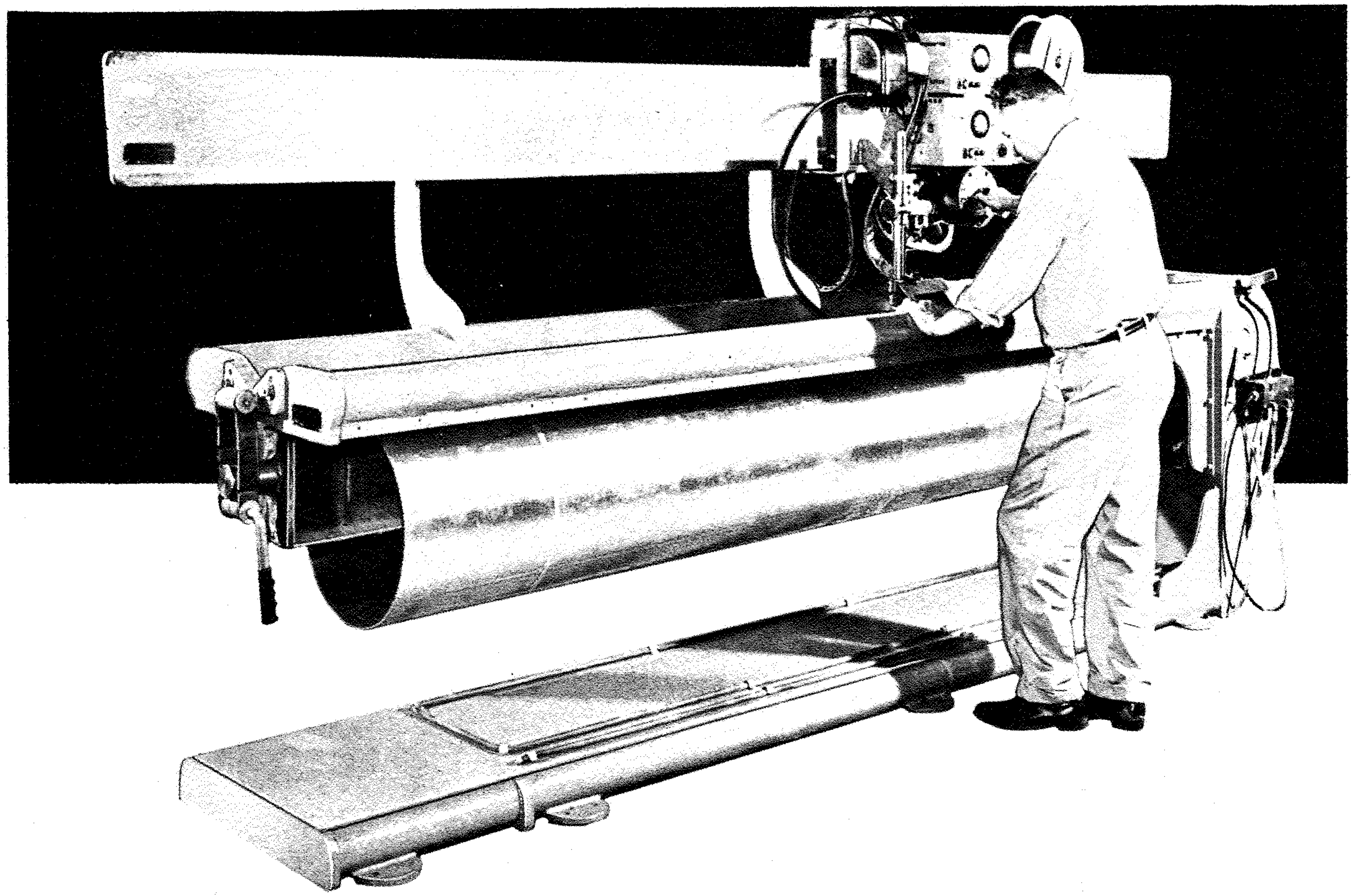


FIGURE 5. "STAKE" FIXTURE

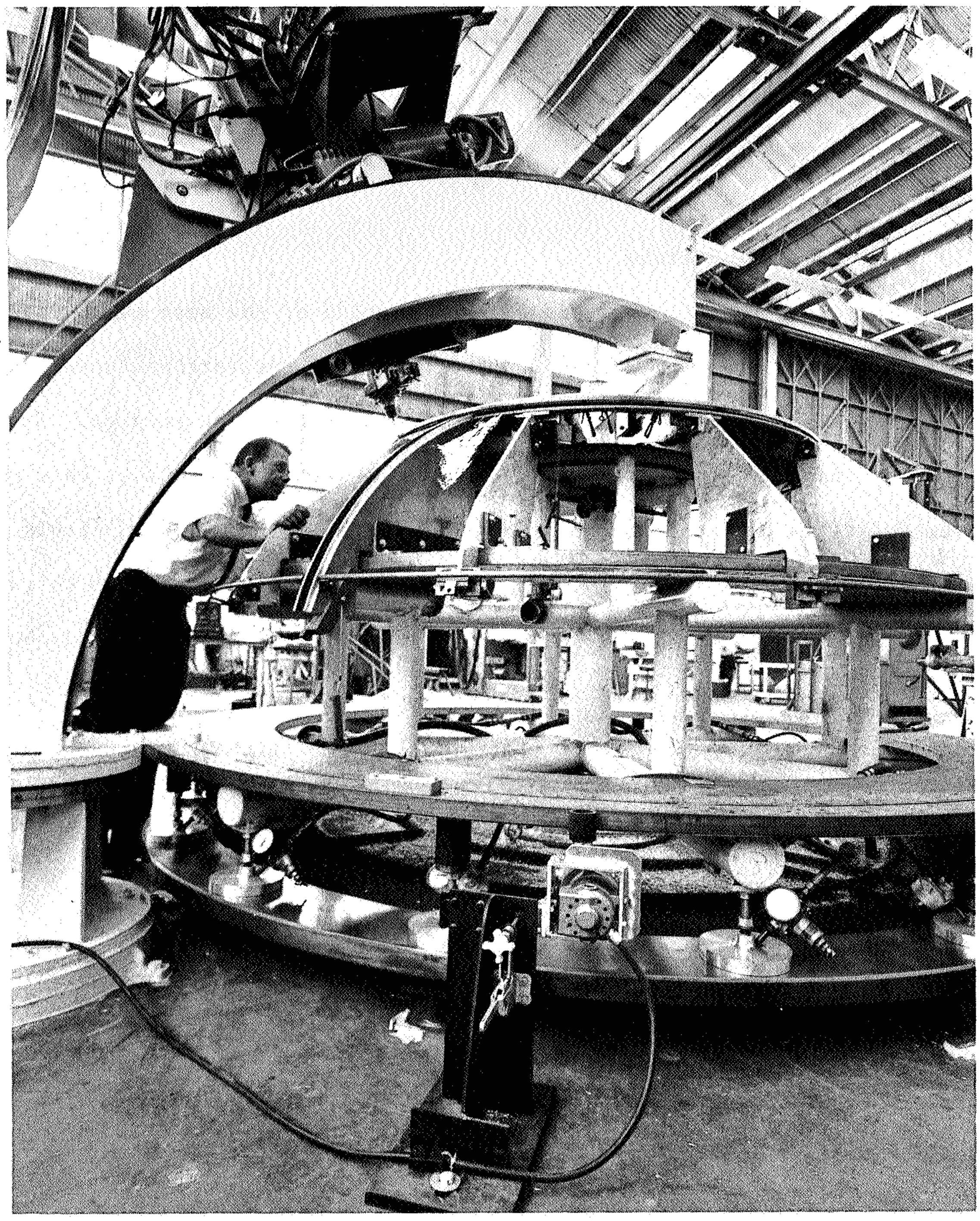


FIGURE 6. SPECIAL JIGGING ASSEMBLY FOR WELDING DOMES FOR STAINLESS STEEL MISSILE TANKAGE
(Courtesy Convair Division, General Dynamics Corporation)

JOINING PROCESSES

Many joining processes can be used for joining stainless steels. These processes fall into three major groups:

(1) Fusion welding

(2) Solid-state bonding

(3) Brazing and soldering.

Fusion-welding processes are those in which a portion of the base metal is melted during the joining operation. These processes include the various types of arc welding, electron-beam welding, plasma welding, and resistance welding. Solid-state bonding includes the processes in which no molten metal, either base metal or filler metal, is produced in the weld joint. Bonding is achieved simply by the diffusion of atoms of the pieces being joined across the interface between the two pieces. In brazing and soldering, a molten filler metal is used, but no melting of the base metal occurs.

The fusion welding processes are the most frequently used methods of joining stainless steel. Brazing stainless steel also is common, but the applications are more limited than those for which fusion welding are used. Solid-state welding is limited to specialized applications.

The various processes are described briefly in Appendix A. Detailed descriptions of the processes and equipment can be found in References 10 and 22.

FUSION WELDING

Fusion-welding processes are those in which substantial amounts of molten metal are produced during the joining operation. Fusion welding processes frequently are thought of being only the arc-welding processes. However, there are other processes that rightfully belong in this category, particularly resistance welding. All of the fusion welding processes that commonly have been used in the fabrication of stainless steel hardware are included in this section. Processes such as electroslag, electrogas, and Narrow-Gap welding are not used with stainless steel so are not covered in this report.

The arc-welding processes have had wide application in joining stainless steels. The most frequently used is the shielded metal-arc process. Gas-shielded tungsten-arc (GTA) and gas-shielded metal-arc (GMA) processes are used to a lesser degree while the use of submerged arc welding is quite limited. Electron-beam welding is finding ever widening acceptance, particularly in the joining of thin sheet. Plasma welding has had only limited use, although the application of plasma for cutting is relatively common.

Resistance spot welding has been used extensively for fabricating stainless steels. Seam welding, projection welding, and flash welding also have been used for these alloys but to a lesser degree.

Shielded Metal-Arc Welding. The shielded metal-arc process (which is also called covered electrode, metal-arc, or stick welding) is the most common method of fusion welding stainless steel. The chief advantages of this process are its versatility and simple equipment requirements. Covered electrodes are available that produce weld deposits with compositions that match all of the common types of stainless steels. Shielded metal-arc welding can be used to weld stainless steel as thin as 1/16 inch as well as heavy plate. Out-of-position welds can be made easily. The only equipment that is required is a power supply, an electrode holder, and connecting cables.

On the negative side, shielded metal-arc welding is slower than some of the other arc-welding processes. Also, the quality of the welded joint depends on the welder's skill and degree of concentration.

Electrodes for use with the shielded metal-arc process were listed in Table I. These electrodes are available with two types of coverings: (1) lime-covered electrodes for welding with d-c reverse (electrode positive) polarity, as shown by the number -15 in the electrode numbering system; e.g., E308-15, and (2) titania-covered electrodes used for welding with either a-c or d-c reverse polarity as shown by the number -16 in the electrode numbering system; e.g., E308-16.

The lime-covered d-c electrodes are preferred for out-of-position welding. The slag that is formed freezes quickly and provides good wetting action by the weld metal; this helps to prevent undercutting. These electrodes are especially suited for making root passes as the weld bead is convex which helps to prevent Cracking when the weld bead cools, Very little spatter is produced. However, this spatter is very adherent and hard to remove.

Most welders prefer the titania-covered electrodes since a smoother and better appearing weld bead can be deposited. The slag is very easy to remove. While titania-covered electrodes can be used for out-of-position welding, they are not as good as the lime-covered electrodes for this purpose.

The covering on these electrodes has a tendency to pick up moisture from the air if the electrodes are not kept in a closed container. Moisture in the coating may cause porosity in the weld metal. Thus, electrodes from freshly opened containers should always be used if possible. If electrodes must be used that have been out of the container for some time, they should be dried in an electrode drying oven. Usually, it is well to keep electrodes in a drying oven after the container is opened. The temperature of the drying oven should follow the electrode manufacturer's recommendations. This is especially important since the wrong temperature can damage the electrode covering. Typically, the electrodes are stored in drying ovens at *225* F ± *50* F after opening (Ref. *24)*. If the electrodes are exposed to moisture, the stainless steel electrodes are heated to 180 F for one hour followed by baking at 350 F for one hour.

Types of Weld Joints. Weld joints in stainless steels should be designed to minimize the amount of weld metal deposited. The weld metal shrinkage experienced with these steels is greater than in carbon or low-alloy steels due to the high thermal expansion of stainless steels. By minimizing the amount of deposited weld metal, weld joint shrinkage and distortion also is minimized.

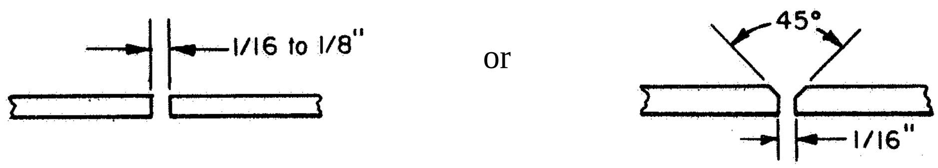
Typical weld joints for the shielded metal-arc welding of stainless steel are illustrated in Figure 7. Root openingsshould be kept as narrow as possible commensurate with full penetration.

In butt welds, square joints can be used in sheet up to 1/8 inch. For stainless steel 3/16 to 1/2 inch thick, the edges of the parts should be beveled to produce a 60-degree V-joint. A switch to a U-groove in plate over 1/2 inch thick requires less weld metal than does a V-groove. The U-groove is more expensive to prepare than the V-groove but the use of less weld metal decreases the amount of distortion. A double-V groove can be used in place of the U-groove if welding can be done from both sides of the joint. Similar rules are followed in designing fillet-weld joints.

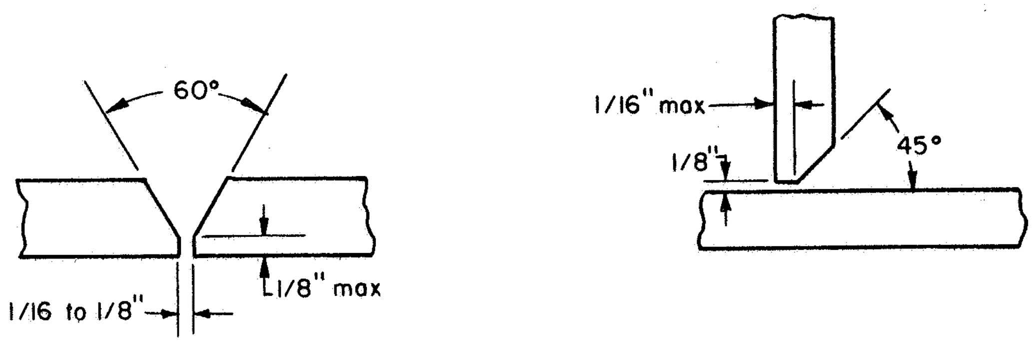
All welds in stainless steel over 1/4 inch thick should be made with a minimum of two passes. In multipass welding, each bead should be cleaned and wire brushed before the next bead is deposited to insure that all slag is removed, The backside of the root bead should be ground to solid metal before welding from the backside of a double-U or double-V joint.

Root passes of weld joints in stainless steel piping frequently are made with a consumable-insert ring. These rings are welded by the GTA process and are discussed in that section of this report. After such a root pass is made, the joint may be completed by the shielded-metal-arc process.

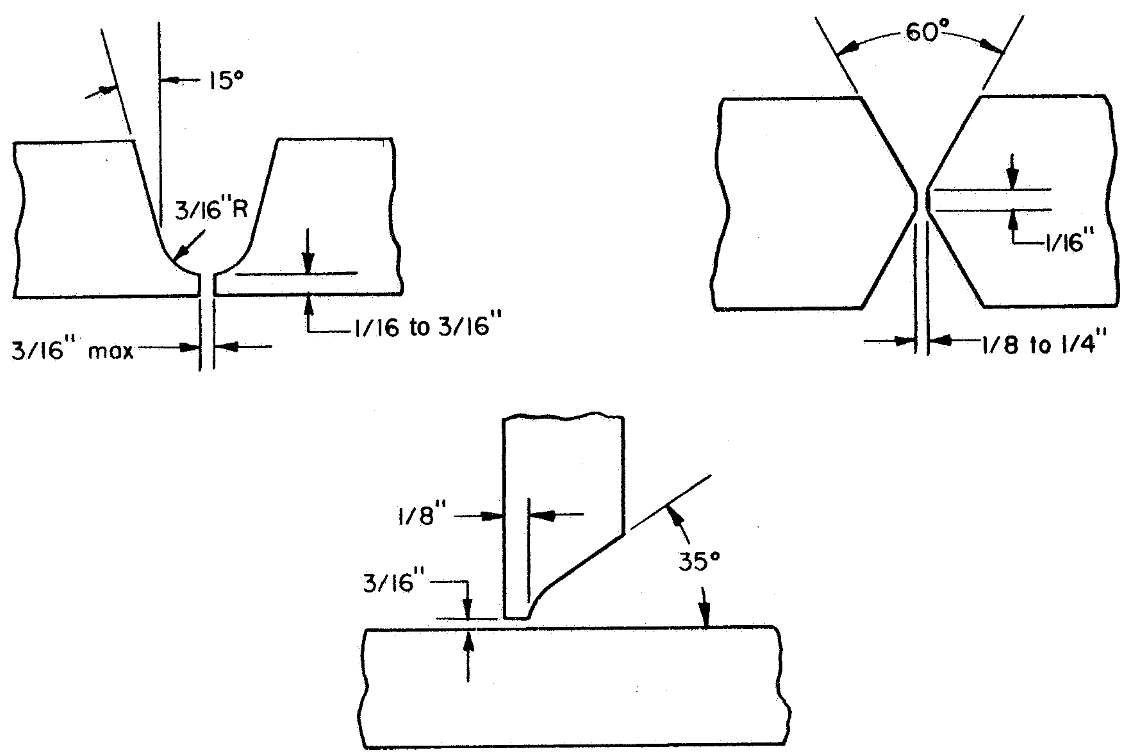
Welding Procedures. No unusual procedures are required for shielded metal-arc welding of stainless steels. The chief requirement is that the arc should be kept as short as possible without touching the molten weld puddle. Alloying



a. 1/8 to 3/16-inch-thick base metal



b. 3/16 to 1/2-inch thick base metal



c. Over 1/2 inch thick

FIGURE 7. TYPICAL WELD JOINTS FOR SHIELDED METAL-ARC WELDING OF STAINLESS STEEL (REF. 10, 11, 15, 25, 26)

elements can be lost if a long arc is used. This is an extremely important point in welding stainless steel as a small change in the chemical composition can result in weld metal cracking or a change in the corrosion resistance of the weld metal.

The electrode should be tilted in the direction of welding. The angle of tilting can be more critical than when welding carbon or low-alloy steel as stainless steel weld metal is less fluid and the volume of slag is greater. The weld beads should be deposited with a string bead technique or with a slight weave. A small amount of weaving is helpful in avoiding trapped slag along the edge of the bead. Excessive weaving should be avoided as this motion can break up the gas and slag shield and alloying elements may be lost. The width of the weave should not exceed 2-1/2 to 3 times the electrode diameter.

The welding speed is important in shielded metal-arc welding of stainless steel. Stainless steel covered electrodes do not have the deep penetration characteristics of many carbon or low-alloy steel electrodes. Thus, full penetration may be difficult to achieve at times. Deeper penetration can be achieved if the travel speed is such that the tip of the electrode is just ahead of the molten puddle. If the welding current is increased to increase penetration, the travel speed should also be increased. Increasing current alone will increase the amount of molten weld metal in the puddle which may actually make deeper penetration harder to achieve.

Typical conditions of voltage and current are given in Table VIII. These conditions should be used only as a guide as optimum conditions will depend on the joint shape and alignment, metal thickness, proximity of chill bars, brand of electrode, and the welder's preference. In general, the welding current should be kept as low as possible with accompanying good fusion and penetration. High welding currents can lead to loss of alloying elements, excessive dilution of the weld metal, or an undesirable bead shape.

When starting the weld, the arc should be struck only in the weld joint where the starting spot will be fused into the weld or on a starting tab. It is good

TABLE VIII. TYPICAL WELDING CONDITIONS FOR STAINLESS STEEL-COVERED ELECTRODES (REF, 25)

Electrode Diameter, inch	Welding Current, amp: Flat, horizontal and overhead	Welding Current, amp: Vertical	Arc Voltage, volts
3/64	15-25	15-25	23
1/16	20-40	25-40	24
5/64	30-60	35-55	24
3/32	45-90	45-65	24
1/8	70-120	70-90	25
5/32	100-160	100-125	26
3/16	130-190	130-145	27
1/4	210-300	--	28
5/16	250-400	--	29

practice not to strike the arc in an existing crater. Arc strikes in any location but these can act as initiation points for cracking and corrosion.

Similarly, the arc should be stopped over the crater or on a runoff tab. The arc should not be carried out of the weld joint before breaking it. Two problems arise if the arc is stopped over the crater. If the crater is not filled before stopping the arc, crater cracking may occur or the center of the crater may have low corrosion resistance due to segregation of alloying elements. If the crater is filled before stopping the arc, the last metal added will not receive adequate protection from oxidation. Several solutions to this problem can be used: (1) the crater area can be ground or chipped out; (2) the size of the crater can be diminished by moving the arc rapidly along the joint; (3) after the arc is stopped and the crater starts to solidify, the arc can be restruck to fill the crater.

Crater cracking is encountered most frequently in a fully austenitic weld metal. Thecolumbium bearing stainless steels such as Type 347 are susceptible to both crater cracking and crater segregation severe enough to affect corrosion resistance.

Applications. Shielded metal-arc welding has been used extensively in fabricating components of nuclear power reactors. Typical of these applications are those at the Dresden Nuclear Power Station near Chicago (Ref. 27). Within the reactor vessel, the support structure for the nuclear core was fabricated from Type 405 ferritic stainless steel. The core support grid of this structure was made of 1-inch-thick plate fillet welded with E312 electrodes. Some porticns of the support structure of necessity had to be heat treated with the reactor vessel itself. E430 electrodes were used for making the welds that would be heat treated. The pump housings were made of Type 316 castings. The housing was cast in two halves which subsequently were welded together. The root pass of these welds were made by GTA welding. The weld was completed using electrodes especially formulated to deposit welds having a ferrite content of about 12 percent (the ferrite content of the casting was 15 percent). Control rods were fabricated from a special 18Cr-12Ni stainless steel containing 2 percent boron. The boron acts as the control material to regulate the nuclear reaction. The 8-1/2-foot-long rods were made of three 3/8-inch-thick plates welded together in a cross-shaped section. Fillet welds between the plates were made with E312 electrodes.

Gas Tungsten-Arc Welding. The manual and automatic GTA process (Figures 8 and 9) is used for welding all types of stainless steel where (1) an arc weld of superior quality must be made, (2) the welding heat must be controlled very accurately, or (3) good as-welded appearance is required. Good GTA welds are free of porosity, slag inclusions, and contamination from oxygen and nitrogen in the air. GTA welds are consistently stronger, more ductile, and have better corrosion resistance than other types of arc welds. With GTA welding, the welding heat, amount of penetration, and bead shape can be very accurately controlled. Interpass or elaborate postwelding cleaning operations are not needed as there is no spatter or slag crust with GTA welds and the bead surface is smooth and uniform. GTA welds can be made without adding filler metal so that bead reinforcement can be minimized.

The GTA process normally is used for welding stainless steel from around 0.005 inch up to 1/4 inch thick. Stainless steel thicker than 1/4 inch can be GTA welded, but this is usually done only for critical applications. Gas metal-arc (GMA) welding is more economical than GTA welding when the stainless steel is thicker than 1/4 inch.

Electrodes for GTA welding of stainless steel are made from either pure tungsten or tungsten alloyed with thorium. The chemical composition of standard tungsten electrodes is listed in Table IX. The thoriated-tungsten are preferred. Compared with pure tungsten, the thoriated electrodes last longer, make arc starting easier, have a more stable arc especially at low currents, and have less tendency to spit off particles of tungsten into the weld metal. Electrodes

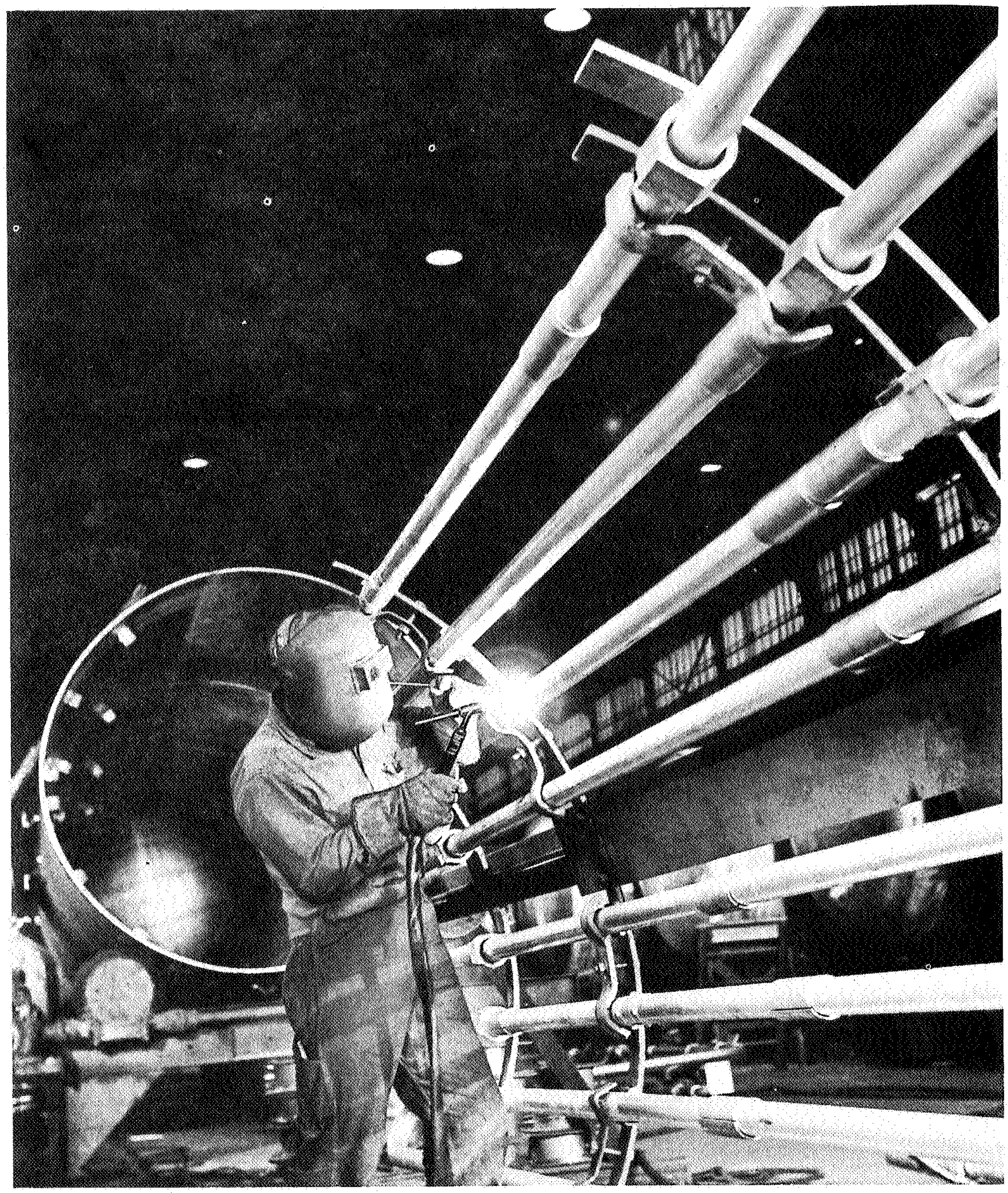


FIGURE 8. MANUAL GTA WELDING OF STAINLESS STEEL PIPING SYSTEM FOR NUCLEAR-POWERED SUBMARINE
(Courtesy Linde Division, Union Carbide Corporation)

FIGURE 9. AUTOMATIC GTA WELDING OF STAINLESS STEEL SHEET (Courtesy Linde Division, Union Carbide Corporation)

TABLE IX. CHEMICAL COMPOSITION OF ELECTRODES FOR GTA WELDING (REF. 28)

AWS-ASTM Classification	Tungsten, minimum, percent	Thorium, percent	Zirconium, percent	Total Other Elements, maximum, percent
EWT	99.5	--	--	0.5
EWTh-1	98.5	0.8-1.2	--	0.5
EWTh-2	97.5	1.7-2.2	--	0.5
EWTh-3	98.95	0.35-0.55	--	0.5
EWZr	99.2	--	0.15-0.40	0.5

containing zirconium are restricted to welding with a-c current where they have better arc starting.

The size of the electrode to use is governed by the amount of welding current that is required to make the weld. The electrode sizes to be used for various levels of welding current are given in Table X. If too large an electrode is used, the arc can be difficult to control. If the electrode is too small, tungsten may be deposited inthe weld metal.

For welding stainless steel, the electrode is ground to a sharp point or to a point having a slightly rounded tip. During welding, a small ball of molten tungsten will form at the end of the electrode. As long as this ball is small, it will not interfere with good arc control. However, if the current is set *too* high for the size of electrode being used, the molten ball will become larger and the arc will be hard to control. A danger also exists that a large molten ball on the end of the electrode may become dislodged and drop into the molten weld puddle. The obvious solution to avoid such tungsten contamination is to use the next larger size of tungsten electrode.

Care must be exercised to avoid contamination of the end of the electrode. Electrode contamination usually is caused by touching the end of the electrode to the molten weld metal. When the electrode is contaminated, a large molten ball of a mixture of tungsten and the base metal will form on the tip of the electrode. If this happens, the welding operation should be halted and the electrode reground to remove the contaminated portion.

Filler wire feeders are used in mechanized and automatic GTA welding to add filler wire to the weld at a closely controlled speed and location. The wire is fed from a spool by motor-driven feed rolls whose speed can be regulated accurately over a wide range. An adjustable metal guide tube directs the wire into the weld puddle at the correct angle and direction. The guide tube usually is attached to the welding torch so that the correct alignment between the electrode and the filler

TABLE X. RECOMMENDED CURRENT RANGES FOR TUNGSTEN AND THORIATED TUNGSTEN ELECTRODES (REF. 29)

Electrode Diameter, inch	Current Range, amperes[a]				
	Direct Current Straight Polarity, Both Pure Tungsten and Thoriated Tungsten	Alternating Current, Unbalanced Wave Power Supply		Alternating Current, Balanced Wave Power Supply	
		Pure Tungsten	Thoriated Tungsten	Pure Tungsten	Thoriated Tungsten
0.040	15-80	10-60	15-80	20-30	20-60
1/16	70-150	50-100	70-150	30-80	60-120
3/32	150-250	100-160	140-235	60-130	100-180
1/8	250-400	150-210	225-325	100-180	160-250

(a) These current values are for argon shielding gas.

wire can be maintained. In manual welding, a foot control usually is used to regulate the welding current. The operator can start the weld at a low current and then build up the current to the desired level during welding by operating the foot control. At the end of the weld, the current can be lowered to eliminate a crater which may otherwise form. Also, the current can be reduced when tying in with a weld already made.

Argon or helium or a mixture of the two gases are used to protect the end of the electrode, the arc, and the molten weld puddle from the atmosphere during welding.

Argon is used for manual GTA welding of stainless steel for several reasons. In argon, the arc is smooth and easy to start and control. Compared with helium, the arc in argon is cooler which means that the weld puddle will be smaller and the welding operator will have better control over penetration. Argon is more economical to use than helium, because it is cheaper and because lower flow rates are used with argon. Since argon is heavier than air, while helium islighter than air, the argon blankets the weld area better than helium. For helium to shield as well as argon, the flow rate must be two to three times that of argon. Argon also provides better shielding if there are any drafts or breezes that might disturb the gas shield.

Helium usually is used for automatic welding because, first, the arc is hotter, and second, the arc length can be controlled more accurately than with argon. The higher heat of helium-shielded arc permits high travel speeds to be used. The travel speed can be increased as much as *40* percent by using helium instead of argon. Automatic GTA welding is frequently used in high production applications, when high travel speeds are important. Occasionally helium may be used for manual GTA welding very thick parts where a great many passes are required to fill the weld joint. By using helium instead of argon, heavier passes can be made and the joint can be completed quicker. In automatic welding, the arc length is controlled through measurement of changes in arc voltage. These changes can be measured more easily when the arc is shielded with helium. Thus, the arc length can be controlled more accurately in helium than in argon.

A mixture of argon and helium is sometimes used in automatic GTA welding. The mixture is usually used to obtain an arc that is less penetrating than the arc obtained with pure helium. A mixture of argon and helium might be used when welding very thin stainless steel to prevent burnthrough. The arc will become cooler as the amount of argon is increased. Usually, mixtures are 25 argon-75 helium, or 50 argon-50 helium. These, as well as other mixtures of argon and helium can be obtained already mixed in tanks from gas suppliers. Special valves and controllers are also available that allow the user to mix the gases in any ratio desired from tanks of pure argon and helium.

The addition of a small amount of hydrogen to argod will produce a hotter arc than pure argon. The hydrogen also reduces undercutting at the edges of the weld bead and helps prevent porosity in the weld metal. The amount of hydrogen that is added may be as high as 35 percent. Mixtures of 15 hydrogen-85 argon and 35 hydrogen-65 argon are available commercially. Republic Steel Corporation fabricates stainless steel tubing by automatic GTA welding using 15 hydrogen-85 argon (Ref. 91). Filler wire is used in GTA welding to fill up a joint that has a V- or U-shape or a joint that has poor fitup. Filler wire should be used when making butt welds in 1/16-inch or thicker material so that the weld will have a good bead reinforcement. Filler wire also should be used when making filler welds. Lap and corner welds require filler wire when the base material is over about 1/8 inch thick.

The diameter of the filler wire that is used will depend upon the thickness of the material to be welded and the current settings. Fillet wire that is too large will take too much of the welding heat to melt it and the weld may lack penetration. If the filler wire is too small, the welder may have difficulty feeding it into the weld pool fast enough to build up the weld bead properly.

Proper guiding of the filler wire into the weld puddle also is important. Weld-metal porosity has been caused by erratic guiding of the wire (Ref. 30). This porosity was eliminated by always guiding the wire into the puddle on the joint centerline and at the puddle leading edge.

Types of Weld Joints. Figure 10 shows recommended butt joints for GTA welding of various ,thicknesses of stainless steel. Fillet weld joints are shown in Figure 11. Lap joints do not need any special preparation except that the pieces must be tightly clamped together. No filler wire is needed for lap joints in stainless steel 1/8 inch thick or less. Corner joints can be made in stainless steel less than about 3/16 inch thick without joint preparation. Stainless steel 1/4 inch or thicker should bebeveled as shown in Figure 12 for a corner joint.

Special techniques are required for making circumferential welds in pipe or tubing. Since these welds can be made from one side only, any defects in the underside of the weld cannot be repaired. The underside of the weld also must have a smooth contour with a minimum amount of reinforcement so that flow through the pipe will not be disturbed. One technique for welding circumferential joints in stainless steel pipe incorporates the use of insert rings.

Consumable insert rings are rings of stainless steel that are placed in the joint root when the two pieces of pipe are fitted together. They are GTA tack welded to hold them in proper alignment. Two types of insert rings are shown in place in Figure 13. Recommended joint dimensions also are given. The root pass is made from the topside of the joint in the normal manner by GTA welding except that no filler wire is added. As the insert melts, the surface tension of the molten metal forms the underside of the bead into the desired contour. After the root pass is made with the consumable-insert ring, the joint may be completed by GTA, GMA, or shielded metal-arc welding. Consumable insert rings are available commercially for most of the austenitic stainless steels. The underside of the insert ring must be protected from the atmosphere during welding by purging the

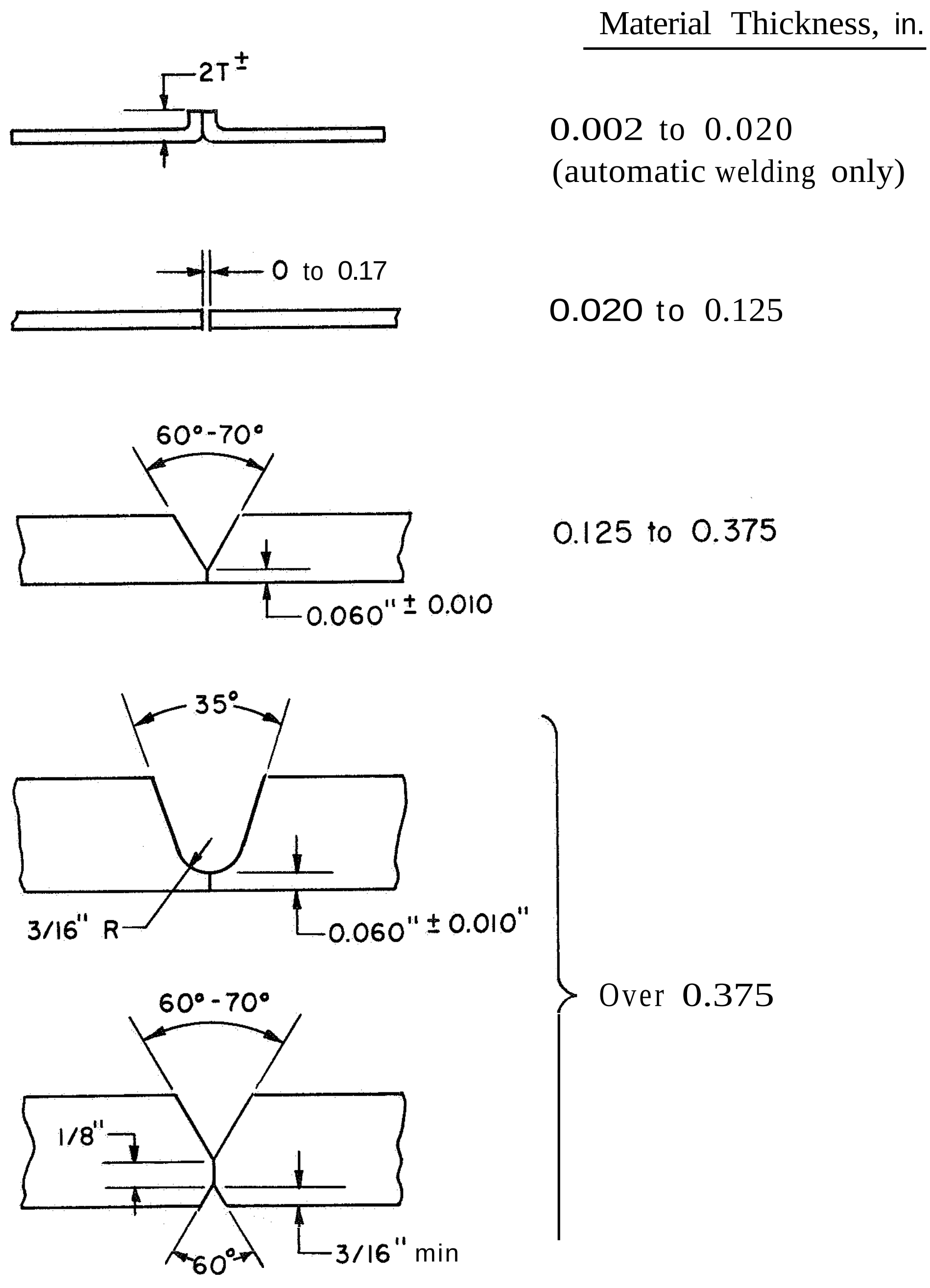
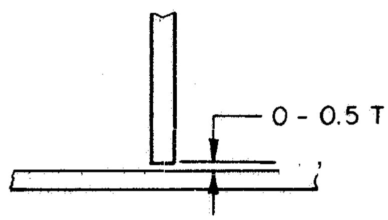
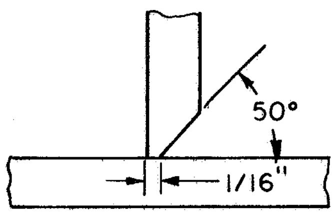


FIGURE 10. TYPICAL BUTT JOINTS FOR GTA WELDING STAINLESS STEEL (REF.31)

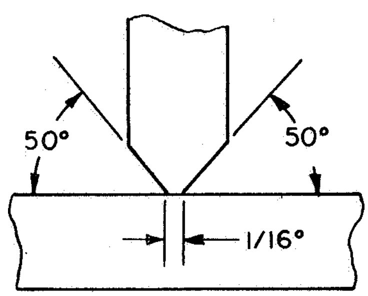
Material Thickness, inches



Up to 3/16



Over 3/16"



Over 1/2"

FIGURE 11. TYPICAL FILLET JOINTS FOR GTA WELDING STAINLESS STEEL (REF. 31)

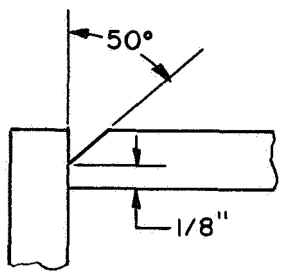


FIGURE 12. CORNER JOINT FOR GTA WELDING STAINLESS STEEL OVER 1/4-INCH THICK (REF. 31)

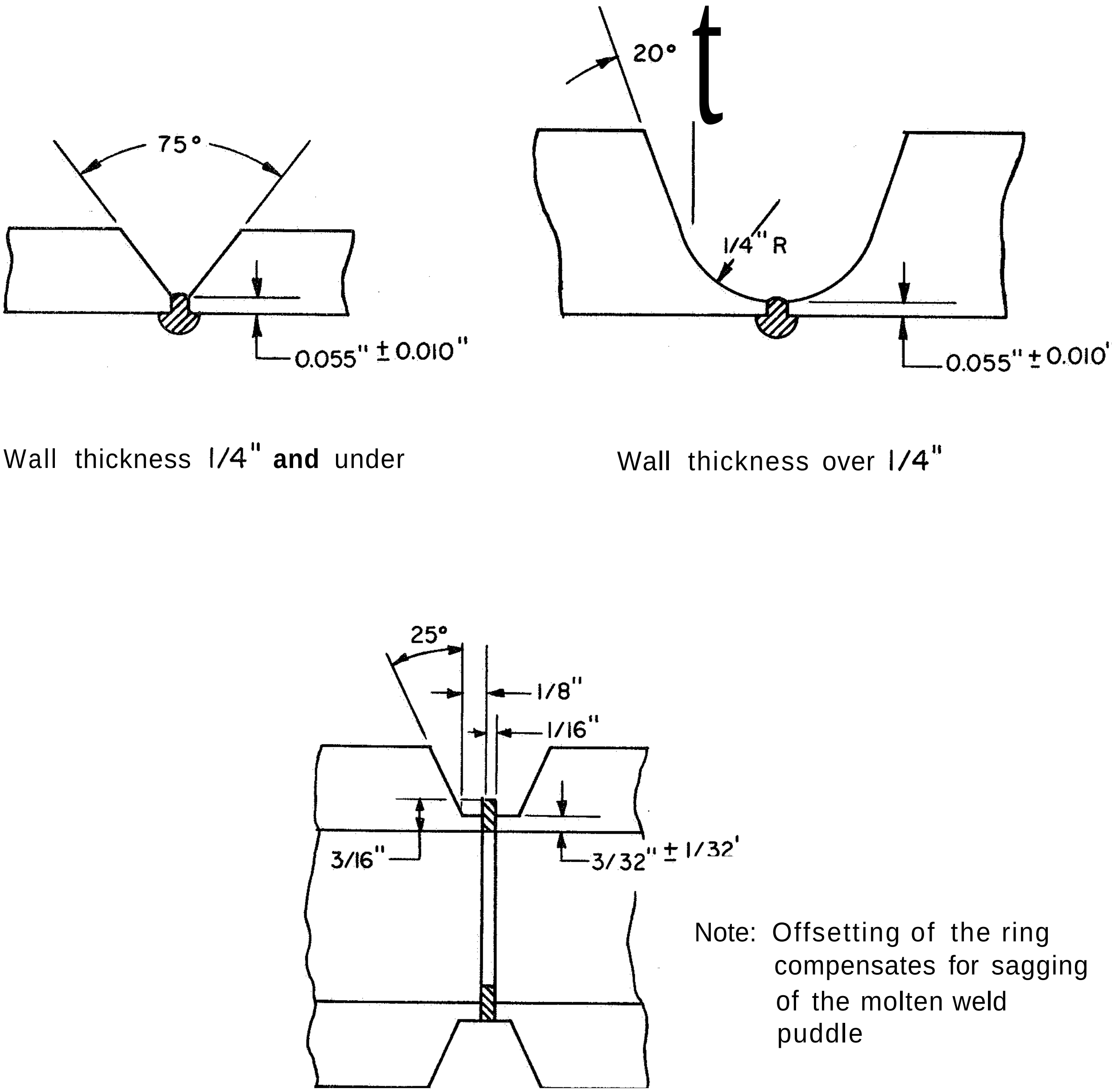


FIGURE 13. TWO TYPES OF CONSUMABLE-INSERT RING FOR FIXED-POSITION WELDING OF PIPE JOINTS (REF. 11, 32)

inside of the pipe with argon before welding (Ref. *32)*. Welding current should be between 75 and 100 amperes with the optimum rate of travel between 2 and 3 inches per minute. The welding current and travel speed control the amount of reinforcement on the underside of the weld. Low currents or high travel speeds mean more reinforcement. A flatter underside results with high current or lower speeds. Detailed instructions on the use of these inserts are available from the supplier.

The weld joint also can be made with an integral lip that acts in the same manner as a consumable insert ring. Such a joint is shown in Figure 14. These joints are expensive to machine, however, and require very careful fitup.

Welding Procedures. The GTA welding of stainless steels requires no unusual welding procedures. However, close control of the welding operation is required to achieve optimum quality welds.

Typical conditions for GTA welding of stainless steels are given in Table XI. These conditions are only a guide as the optimum combination of conditions will vary depending on whether welding is manual or automatic, the type of weld tooling used, operator preference, etc.

Protection of the underside of the weld joint always is necessary to prevent oxidation of the backside of the weld and to insure smooth contour of the weld metal on the backside of the joint. The most common way of protecting the backside of the weld joint is to use a grooved copper bar. The pieces being welded are held tightly against the bar with clamps. By drawing heat away from the weld zone, the copper backup bar prevents burnthrough to the joint. If too much metal should be melted, the backup bar will support the molten metal and prevent it from dripping through the joint. If the backup bar is not used, the underside of the weld bead would be open to the atmosphere and could pick up contaminants from the air. For welding light gage stainless steel, better protec-

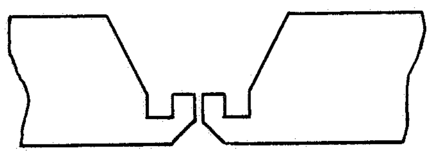


FIGURE 14. JOINT WITH FORMED ROOT USED IN WELDING STAINLESS STEEL PIPE (REF. 10)

TABLE XI. CONDITIONS FOR GTA WELDING OF STAINLESS STEEL (REF. 31)

Thickness, inch	Type of Joint	Welding Current(1) amps Flat	Vertical(2)	Overhead	Electrode Diameter, inch	Welding Speed, ipm	Filler Wire Diameter, inch	Argon Flow, cfh
1/16	Butt	80-100	70-90	70-90	1/16	12	1/16	11
	Lap	100-120	80-100	80-100	1/16	10	1/16	11
	Corner	80-100	70-90	70-90	1/16	12	1/16	11
	Fillet	90-110	80-100	80-100	1/16	10	1/16	11
3/32	Butt	100-120	90-110	90-110	1/16	12	1/16-3/32	11
	Lap	110-130	100-120	100-120	1/16	10	1/16-3/32	11
	Corner	100-120	90-110	90-110	1/16	12	1/16-3/32	11
	Fillet	1.10-130	100-120	100-120	1/16	10	1/16-3/32	11
1/8	Butt	120-140	110-130	105-125	1/16	12	3/32	11
	Lap	130-150	120-140	120-140	1/16	10	3/32	11
	Corner	120-140	110-130	115-135	1/16	12	3/32	11
	Fillet	130-150	115-135	120-140	1/16	10	3/32	11
3/16	Butt	200-250	150-200	150-200	3/32	10	1/8	13
	Lap	225-275	175-225	175-225	3/32,1/8	8	1/8	13
	Corner	200-250	150-200	150-200	3/32	10	1/8	13
	Fillet	225-275	175-225	175-225	3/32,1/8	8	1/8	13
1/4	Butt	275-350	200-250	200-250	1/8	--	3/16	13
	Lap	300-375	225-275	225-275	1/8	--	3/16	13
	Corner	275-350	200-250	200-250	1/8	--	3/16	13
	Fillet	300-375	225-275	225-275	1/8	--	3/16	13
1/2	Butt	350-450	225-275	225-275	1/8,3/16	--	1/4	15
	Lapp	375-475	230-280	230-280	1/8,3/16	--	1/4	15
	Corner	375-475	320-280	230-280	1/8,3/16	--	1/4	15

(1) Direct Current, Straight Polarity

(2) Upward Direction of Welding

tion is obtained by reducing the size of the groove in the copper backup bar. For general welding of these thicknesses of material the groove should be about 3/32 inch wide and about 0.15 inch deep,

For critical applications, the dimensions of the groove in the copper backup bar are important. The chilling effect of the backup bar varies inversely with the width of the groove. This, in turn, affects the width of the fusion and heat-affected zones of the weld joint. Ling-Temco-Vought has specified the width of the groove for various thicknesses of Type 321 stainless steel sheet so that uniform weld joint widths will be obtained (Ref. 30). These dimensions are given in Table XII.

Cooling of the weld joint also is affected by the spacing of the hold-down clamps. Ling-Temco-Vought has specified this spacing also and these dimensions are included in Table XVII. The hold-down bars were made of copper and were continuous for material thinner than 0.060 inch. Segmented bars we're used on thicker material with the spacing between segments being less than 0.010 inch.

Grooved copper backup bars permit only the air contained in the groove itself to contact the underside of the joint. Shielding of the underside of the weld can be improved further by using a gas-shielding backup bar. Such a backup bar has provision for flowing argon or helium into the backup bar groove and thus, only an inert gas comes in contact with the underside of the bead. A typical gas-shielding backup is shown in Figure 15.

Before making circumferential welds in pipe or tubing, the interior of the pipe or tubing should be purged with argon, helium, or nitrogen. As a general rule, adequate purging requires passing through the system a volume of gas equal to about six times the volume of the system. Purging times for various diameters of stainless steel pipe are given in Table XIII. To conserve gas when welding

TABLE XII. DIMENSIONS FOR TOOLING FOR GTA WELDING OF TYPE 321 SHEET (REF. 33)

Sheet Thickness, inch	Backup Bar Groove Width, inch	Backup Bar Groove Depth, inch	Hold-down Clamp Spacing, inch
0.020	0.050	0.020	0.11
0.040	0.090	0.025	0.14
0.060	0.120	0.035	0.14
0.080	0.150	0.040	0.23
0.100	0.165	0.050	0.275
0.120	0.185	0.055	0.32

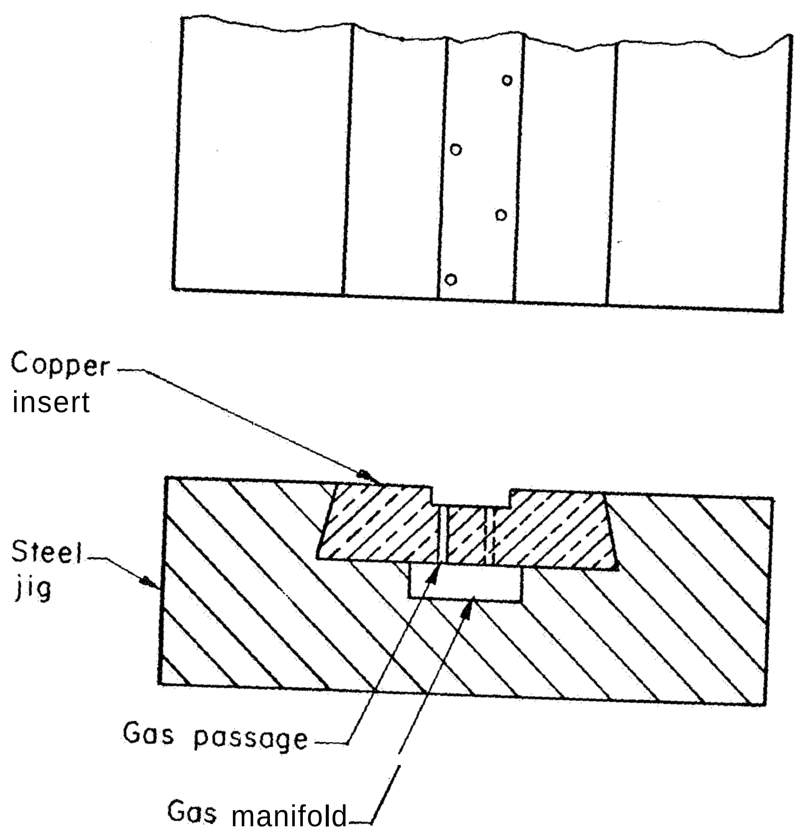


FIGURE 15. TYPICAL BACKUP BAR WITH GAS BACKING

TABLE XIII. PURGING TIMES FOR PIPING SYSTEMS
(6 volumes displacement based on gas flow of
20 cfh)

Inside Diameter of Pipe, inch	Time of Purge per Foot of System Length
1/2	2 sec
1	8 sec
2	24 sec
3	55 sec
4	1 min 30 sec
5	2 min 30 sec
6	3 min 35 sec
8	6 min 0 sec
10	10 min 0 sec
12	13 min 30 sec

large-diameter pipe, a collapsible copper backup bar with a groove for gas passage can be clamped to the inside of the joint. After purging is completed and welding is begun, the backing gas should continue to flow but at a reduced rate. A gas flow of 2 to 5 cfh usually is adequate. If the pressure is too high, the underside of the weld joint will have a concave shape or molten weld metal may be blown out of the joint.

For best results, the arc should be started on a block of stainless steel or copper. Carbon starting blocks should never be used. The use of a starting tab permits the arc to become steady before welding of the joint is begun and allows the operator to observe and correct any irregularities in the arc's behavior. If possible, the arc should be initiated by high-frequency starting rather than touch starting to avoid electrode contamination. If a starting block cannot be used and the arc must be struck inthe weld joint, it should be started a short distance from the end of the joint and welded to the end of the joint. Then start the main weld at the spot that the short weld was started and proceed along the joint. If the weld is started at the end of the joint, a crack may form. The use of the short weld prevents this. The weld should end on a runoff tab so that the crater will not be formed in the weld joint. If it is impossible to end the weld outside of the joint (as in a circumferential pipe weld), the crater should be filled in before breaking the arc. If the crater is left unfilled, a small hole or indentation will be left in the center of the crater. This is a characteristic of GTA welds. The unfilled crater also can act as a source of cracks or corrosion. A foot control can be used to reduce the welding current to minimize the size of the crater.

Precautions. During the course of making the weld, several difficulties may be encountered. The more common of these include arc wander, tungsten pickup, disruption of the gas shielding, and lack of penetration.

Arc wander is the name given when the arc moves from one side of the joint to the other instead of playing on its centerline. Arc wander in GTA welding of 'stainless steel can be caused by a contaminated electrode, a blunt electrode, a magnetic field, or air drafts. Arc wander due to a contaminated or blunt electrode usually is a rapid movement of the arc from one side of the joint to the other. If the arc moves back and forth slowly or stays on one side of the joint, magnetic fields or air drafts are probably the cause. Arc movement caused by a magnetic field usually can be solved, or at least minimized, by changing the position of the ground cable attachment. Sometimes steel jaws of hold-down clamps become aagnetized and also can disrupt the arc.

Bits of tungsten can be picked up in the weld metal if the arc is struck on the workpiece or if the welding current is too high. Starting the arc by touching the electrode to the workpiece can cause the tip of the electrode to weld itself to the work just as the two touch. As the electrode is withdrawn to start the arc, a bit of electrode will break off and remain in the joint. This can be prevented by using the high-frequency starting or by starting the arc on a starting tab.

If the inert gas shield is not performing properly, air will come in contact with the molten weld metal and hot base plate and cause contamination. The gas shield can break down for several reasons: (1) the flow of shielding gas is too low and the weld metal is not completely protected, (2) the flow of shielding gas is too high and turbulence is created which sucks air into the shielding gas, (3) drafts can blow the shielding gas away, *(4)* the gas-supply hose fittings or gas passages in the torch are blocked or loose. Extra care must be exercised when GTA welding outside corner joints. The configuration of the parts acts as a wedge to deflect the flow of shielding gas away from the weld puddle. Good shielding can be obtained by increasing the gas flow, using a larger gas cup on the torch, and withdrawing the tungsten electrode into the torch slightly. Welding in the vertical-up direction improves the gas shielding somewhat also.

A weld joint that shows lack of penetration is not getting eough welding heat. This usually means that the current is too low or the travel speed is too high. In GTA welding this can also mean that the diameter of the filler wire is too big or that the filler wire is being dipped into the weld puddle too frequently. Too much of the welding heat then is being taken to melt the filler wire. To get proper penetration, the welding current, travel speed, filler wire size, and filler wire feeding rate must be carefully balanced.

Applications. North American Aviation, Inc., has developed special equipment and procedures for automatic GTA welding of stainless steel tubing in the size range of 1/4 inch to 12 inch diameter by 0.005 to 0.125-inch wall thickness (Ref. *34)*. Two types of welding equipment were designed for welding the tubing externally or internally.

The external welding tool is shown in Figures 16 and 17. This tool is of a split design so that it can be installed over the juncture of the two pieces of tubing being joined. A union is placed over the juncture prior to positioning of the tool. Joining is affected by melt-through welding of the union to the two pieces of tubing. The welding tool consists of two basic parts, a holding fixture and a rotor. The holding fixture aligns the tubes, centers the union over the joint, and holds the parts during the welding operation. The rotor contains two tungsten electrodes. During welding, the rotor rotates around the joint moving the electrodes around the circumference of the union. The rotor is gear driven through a flexible, motor-driven shaft.

The internal welding tool (Figure 18) is used to automatically weld a bulkhead feedthrough tube to a bulkhead fitting. The tungsten electrode is mounted on the end of a probe. The probe is inserted into the tubing so that the tungsten electrode is positioned over the joint. A ceramic spacer at the end of the probe

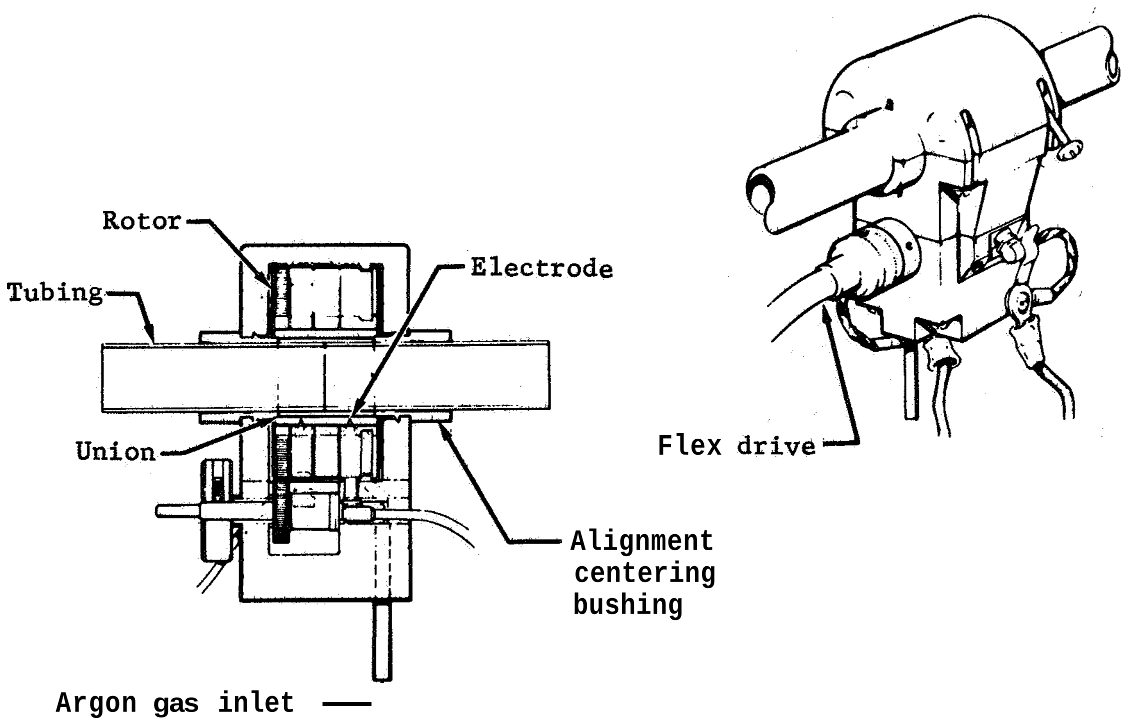


FIGURE 16. DIAGRAM OF EXTERNAL WELDING TOOL FOR GTA WELDING STAINLESS **STEEL** TUBING (REF.34)

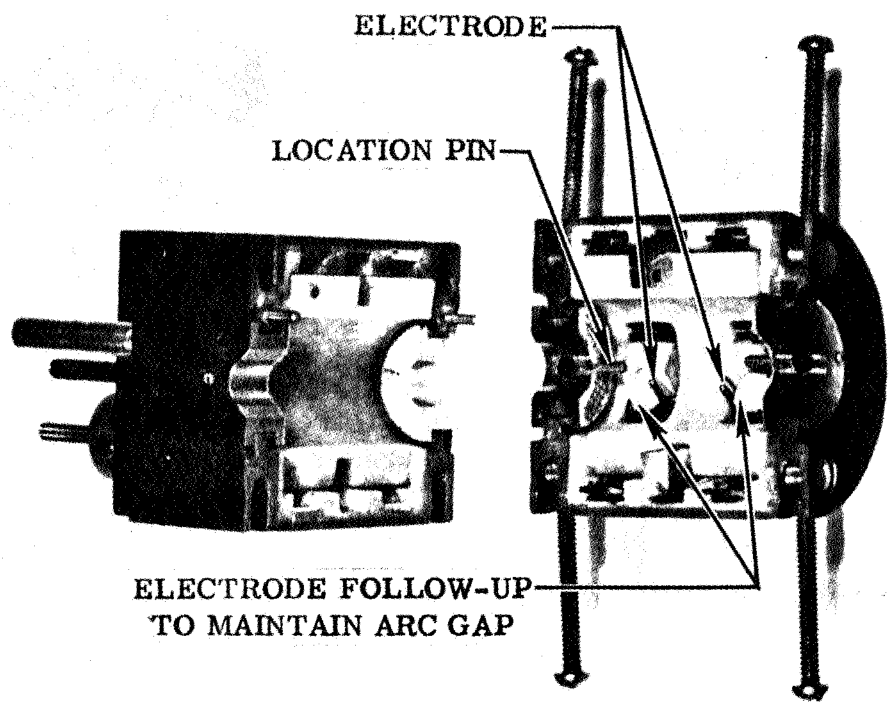


FIGURE 17. PHOTOGRAPH OF EXTERNAL WELDING TOOL FOR GTA WELDING STAINLESS STEEL TUBING (REF.34)

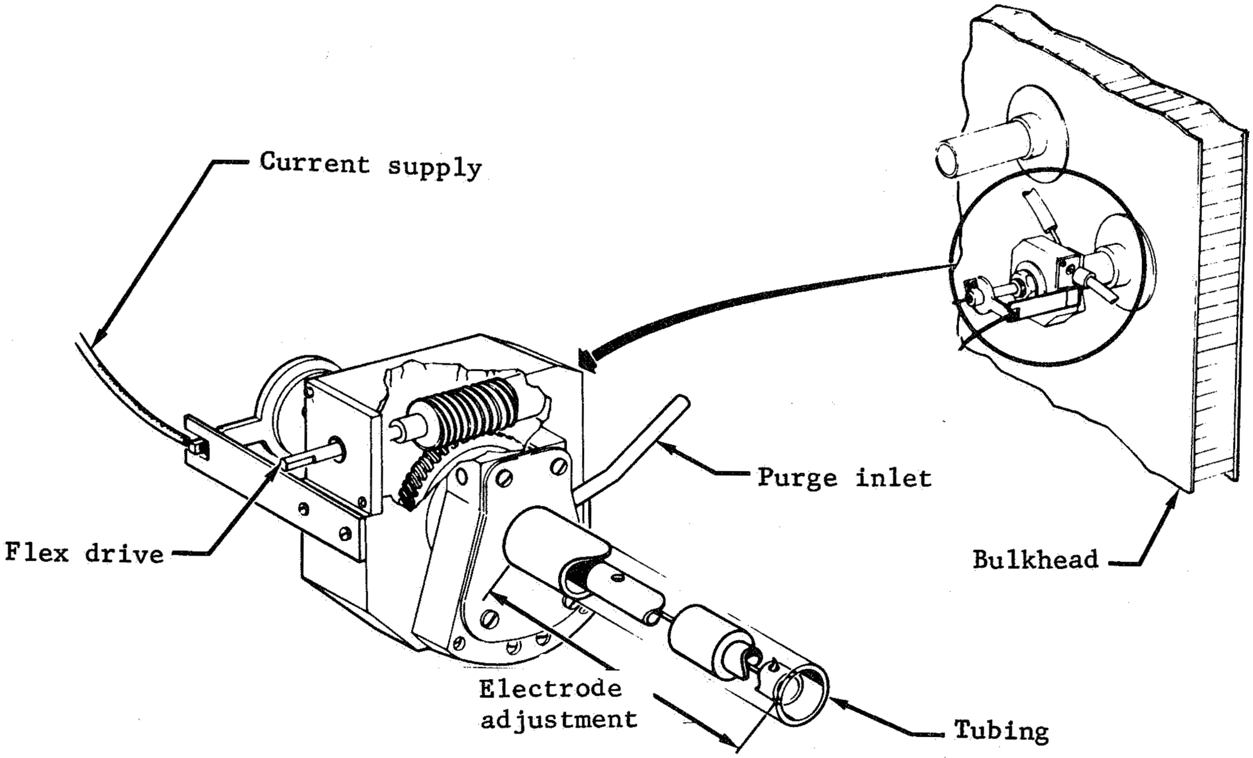


FIGURE 18. INTERNAL WELDING TOOL FOR GTA WELDING STAINLESS STEEL TUBING (REF.34)

guides and centers the probe to maintain a given arc gap between the electrodes and the tube. During welding, the probe rotates moving the electrode around the inside of the joint, making a butt weld between the ends of the tubes.

Cleanliness and precise cantrol of the welding conditions are essential to the production of high-quality welds with these tools. The steps in making external welds are outlined in Figure 19, The various welding parameters (welding current, upslope time, travel speed, downslope time, etc.) are controlled automatically.

Welding devices similar to these developed by North American Aviation now are available commercially.

Arc-Spot Welding. The gas tungsten-arc process has been adapted to make fusion spot welds in stainless steel sheet. The arc-spot weld is like a resistance-spot weld, except that the metal which is melted extends through to the surface of the top sheet and penetrates more deeply into the bottom sheet. This is because the melting actually starts at: the surface of the top sheet where the arc strikes and works down into the bottom sheet.

All classes of stainless steel can be GTA arc-spot welded. The normal thickness range for the top sheet that can be welded is from 0.020 to 0.090 inch. The top sheet can be as thick as 1/8 inch if careful control of all of the welding conditions is maintained. Generally, there is no thickness limitation on the bottom sheet. However, if the top sheet is in the range of 0.090 to 1/8 inch, the bottom sheet should be no thicker than 1/2 inch. If either the top or bottom sheets exceed these limits, correct heating to insure adequate penetration cannot be obtained (Ref. 35).

Arc-spot welding is most frequently applied as a replacement for resistance-spot welding. It has several advantages over resistance-spot welding. Arc-spot welding can be used when there is access to only one side of the assembly being

Form and size tube ends

Vapor degrease and rinse tube ends and unions

Electroetch markings on tube ends to locate welding tool

Electrolytic clean tube ends and unions

Assemble joint

Position welding tool on joint

Purge joint area internally and externally with argon

Adjust welding controls per certification

Weld

FIGURE 19. STEPS REQUIRED IN MAKING AUTOMATIC EXTERNAL TUBING WELDS (REF. 62)

welded. Only enough welding force is required to hold the pieces together; no forging pressure is required as in resistance welding. Arc-spot welding equipment is highly portable. Large assemblies do not have to be moved for successive welds. Thin sheet can be welded readily to thick parts. Finally, arc-spot welding equipment costs much less than does a resistance-spot welder.

Precise timing of the welding operation is required to control the amount of penetration of the bottom sheet. Timing devices are incorporated into the control systems that are used to regulate the various welding conditions. In GTA spot welding, the timer controls the arc time.

A special torch is used for arc-spot welding. It is made more ruggedly than the torch for conventional GTA welding and has a pistol grip. This type of construction enables the operator to hold the torch tightly against the part being welded. Special nozzles are used that have holes around the edge to permit the shielding gas and any gases or fumes generated during welding to escape. Special nozzle configurations also are availble for welding in tight corners and for making tack welds in T or corner joints.

Either argon or helium shielding gases or a mixture of the two may be used. Helium provides greater penetration with a smaller weld-spot diameter than does argon. Argon is generally used when the top sheet is thinner than 1/16 inch and no joint backing is used. When the top sheet is thicker than 1/16 inch or whenever joint backing is used, helium is used as the shielding gas. Sometimes a mixture of about 2 parts of helium and 1 part of argon is used for arc-spot welding stainless steel.

The pieces being arc-spot welded must be held tightly together during the welding operations to obtain good heat transfer between the parts. A weld between the parts that are in loose contact or that may be separated slightly will be smaller than desired if, indeed, a weld is actually made. If the bottom sheet is thin, it may not be stiff enough to provide the support necessary to obtain good contact. When this is the case, additional support for the bottom piece is required. A copper backing bar is the best means of supporting the back piece. If a steel backing bar is used, there is danger of melting through the bottom piece and welding to the backing bar.

The important welding conditions that must be preselected are arc length, welding current, and welding time (Ref. 36).

An increase in the arc length will increase the surface diameter of the spot weld but decrease its penetration into the bottom sheet. If the arc length is set too short, arc starting may be erratic and the electrode may freeze to the weld. Excessive arc length will result in a weak weld because the penetration into the bottom part will be very shallow.

An increase in the welding current will increase the depth of penetration into the bottom part if the parts are of approximately the same thickness. The diameter of the weld also will be increased slightly. If the bottom part is considerably thicker than the top part, increasing the current will increase the weld diameter with little increase in penetration.

Increasing the weld time will increase the diameter of the weld but will have little effect on the depth of penetration.

Convair-Astronautics has used GTA spot welding in the fabrication of the Atlas and Centaur missiles to attach stainless steel covers over access ports, structural members (fuel ducts, angles, etc.) to unsupported skin, and to add pieces after engineering changes are made (Ref, 37). Arc-spot welds of reproducible quality are insured by using a very stable power supply and electronic control circuits to time the weld cycle. Nugget diameter can be controlled to within 3 percent. Figure 20 shows a rectangular doubler being GTA spot welded onto the outer skin of an Atlas.

GTA spot welding frequently is used to attach stiffeners to thin stainless steel sheet. Stiffeners are being arc-spot welded to a stainless steel destroyer stack in Figure 21.

FIGURE 20. GTA SPOT WELDING OF STAINLESS STEEL DOUBLER SHEET ON ATLAS MISSILE SKIN
(Courtesy Convair Division, General Dynamics Corporation)

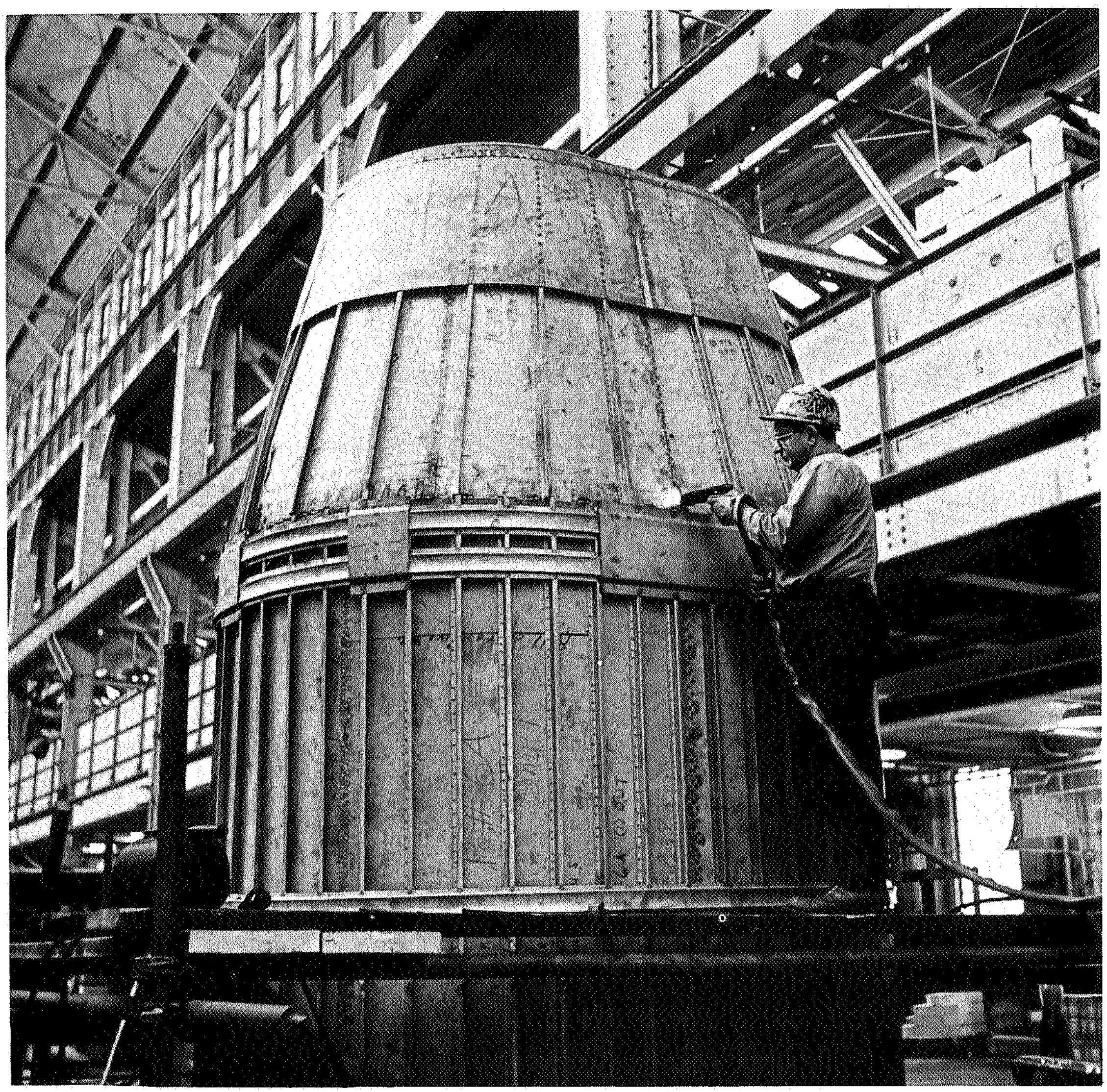


FIGURE 21. GTA SPOT WELDING STIFFENERS TO STAINLESS STEEL DESTROYER STACK
(Courtesy Linde Division, Union Carbide Corporation)

Gas Metal-Arc Welding. The GMA process is used for welding all types of stainless steels, from 1/32-inch sheet to plate an inch or more thick. The same techniques are used for GMA welding stainless steel as are used for carbon steel. About the only difference is that the wire electrode must be stainless steel instead of carbon steel. Some restrictions are placed on the type of shielding gas that is used for GMA welding of stainless steel. Carbon dioxide is not used for welding stainless steel with the same freedom as it is used for welding carbon steel as the corrosion resistance of the weld metal would suffer due to carbon pickup. Carbon dioxide, when used, is an addition to the inert shielding gases.

There are two types of GMA welding: spray-transfer and short-circuiting. The chief difference between these two types of GMA welding is the manner in which the molten metal from the electrode is transferred to the weld puddle. In spray transfer GMA welding, the metal transfers in the form of a spray of fine metal droplets. In short-circuiting GMA welding, the end of the electrode rapidly and repeatedly touches the weld puddle (short circuits). Each time it touches the puddle, some of the electrode wire melts off into the puddle.

Both types of GMA welding are used for welding stainless steel. Since the characteristics and applications of each type differ, they are discussed separately in the following sections.

Spray-Transfer GMA Welding. Spray-transfer is the more common of the two GMA welding processes. The process may be either fully automatic or semiautomatic with the welder manipulating the torch manually. In both cases, the electrode wire is fed mechanically from a coil through the welding gun to the arc.

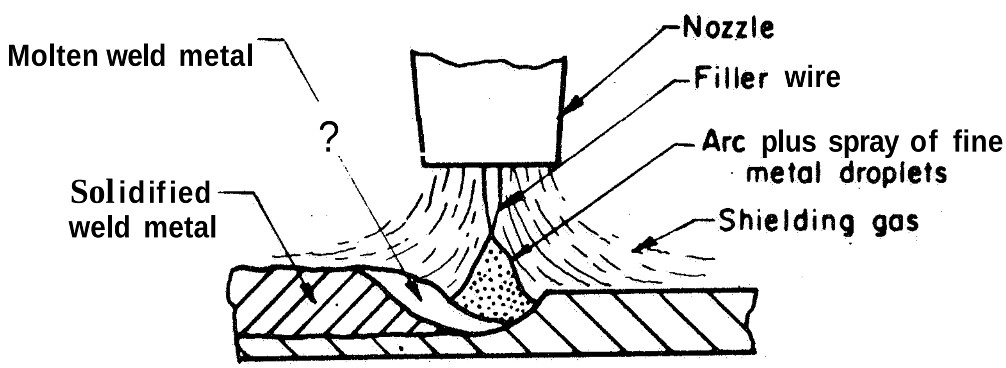
The high welding currents used in spray transfer GMA welding prevent the welding of thin stainless steel sheet. Stainless steel 1/4-inch-thick is the thinnest that can be welded practically, although sheet as thin as 1/8 inch can be welded if considerable care is used. Maximum thickness usually is around 2 inches. For plate thicker than this, submerged-arc welding would be used.

The major advantage of spray-transfer GMA welding is that high-quality welds can be produced at high welding speeds. Spray-transfer GMA welds can be made much faster than covered electrode welds. Since a flux is not used, there is no chance for the entrapment of slag in the weld metal. The inert-gas shield protects the arc so well that there is very little loss of alloying elements as the metal moves across the arc from the electrode wire to the weld metal. Spray-transfer GMA welding, however, is generally restricted to use in the flat or horizontal positions. Satisfactory welds are very difficult if not impossible to achieve in the vertical or overhead positions.

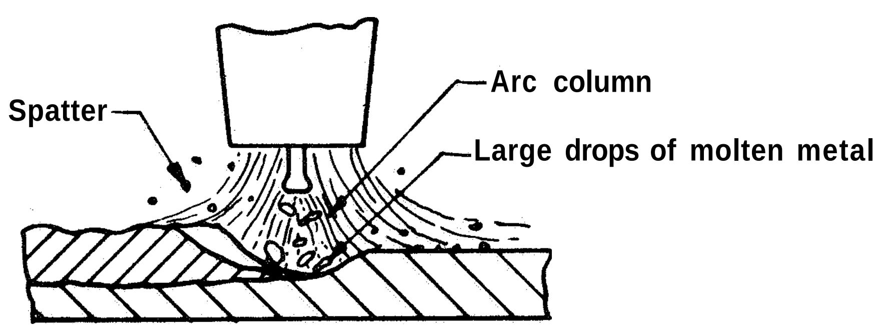
The metal that is melted off the end of the electrode filler wire transfers across the welding arc to the weld puddle as a spray of very fine metal droplets (thus, the name "spray-transfer"). These droplets are too fine to be seen individually. The droplets are interspersed in the arc itself and the combined arc-metal spray has the shape of an inverted cone. The end of the electrode takes on a pointed shape as it melts.

Two electrical requirements must be met if spray transfer is to be achieved: (1) reverse-polarity direct current must be used, and (2) the welding current must be above a certain critical level. Globular rather than spray transfer will occur if either of these requirements is neglected (Figure 22). In globular transfer, large balls of molten metal will build up on the end of the electrode and drop into the weld puddle. When this occurs, the arc is hard to control, penetration and bead shape are poor, and there is a lot of spatter. The critical level of welding current depends on the size of electrode filler wire that is being used. Higher currents must be used for larger wire to obtain spray transfer.

Short-circuiting GMA Welding. Although this type of GMA welding is not used as much as spray-transfer GMA welding, its popularity is growing rapidly.



a. Spray Transfer



b. Globular Transfer

FIGURE 22. GAS-SHIELDED METAL-ARC WELDING WITH SPRAY AND GLOBULAR TRANSFER

Short-circuiting GMA welding differs from spray-transfer GMA welding chiefly in the method by which the molten metal is transferred from the end of the filler wire to the weld puddle. Otherwise, the processes are similar: the electrode filler wire is fed automatically through the welding gun from a coil to the arc with an inert gas shielding the arc, end of the filler wire, and weld puddle from the atmosphere.

Due to a combination of low heat input and the method of metal transfer, short-circuiting GMA welding is well suited for the welding of thin stainless steel sheet. Stainless steel as thin as 1/32 inch can be welded by this process. The maximum thickness of stainless steel welded is about 1/4 inch. This is because the metal deposition rate is lower than that obtained with spray-transfer GMA welding and welding speeds would be too low when welding thicker material by short-circuiting GMA welding.

The chief advantage of the short-circuiting GMA welding process is the ability to weld stainless steel sheet at high speeds. Welding speeds are higher than those used for GTA welding, the other process usually used for arc welding stainless steel sheet, Short-circuiting GMA welding can be done in all positions. Since the heat input is low, distortion due to welding is also low. Joint fitup is not critical. Joints with wide gaps can be welded since the weld metal freezes rapidly and the joint gap can be bridged without melting through the joint. For many applications, a mixture of argon and carbon dioxide can be used for the shielding gas. This mixture is cheaper than the pure argon used for GTA welding. Very little, if any, spatter occurs, so postwelding cleanup is easier. High travel speeds, cheaper shielding gas, less cleanup, and less critical joint fitup combine to make short-circuiting GMA welding more economical than GTA welding.

The action of the arc and the method of metal transfer in short-circuiting GMA welding is different from other types of arc welding. The welding current is below the level required for spray-transfer. As the end of the filler wire melts, the metal does not spray across the arc but builds up in a ball on the end of the wire (Figure 23). This ball builds up in size until it touches the weld puddle, extinguishing the arc, and creates a short circuit. When the short circuit occurs, the welding current increases rapidly, causing the drop of molten metal to be "pinched" off from the end of the filler wire. The arc is reinitiated and the process repeats. The short-circuiting action is very rapid. As many as 200 short circuits a second may occur.

Equipment. The equipment needed for GMA welding includes a power supply, a welding gun, a mechanism for feeding the filler wire, a set of controls, and a shielding gas.

Two types of power sources are used for spray-transfer GMA welding. These are the constant-current drooping-voltage type and the constant-voltage type, with the constant-voltage type finding the widest use. Motor generator or d-c rectifier power sources of either type may be used. Constant-voltage power supplies with a variable-inductance control device are used for short-circuiting GMA welding. The control device introduces a variable amount of inductance into the welding circuit. Theinductance slows down the rate of current increase when the electrode touches the weld pool. Without inductance, the current would increase so rapidly that the end of the wire would be literally exploded away, creating excess spatter. With inductance, the end of the wire is pinched off gently allowing the arc to restart without spatter.

Both manual (usually called semi-automatic) and automatic welding guns are available. Both manual and automatic guns have a nozzle for directing the shielding gas around the arc and over the weld puddle. The wire passes through a copper contact tube, located in the nozzle, where it picks up the welding current.

Manual guns differ in design in the manner in which the electrode wire is fed. Some manual welding guns contain the wire-driving mechanism in the gun proper. These are called "pull" guns because they pull the wire into the gun.

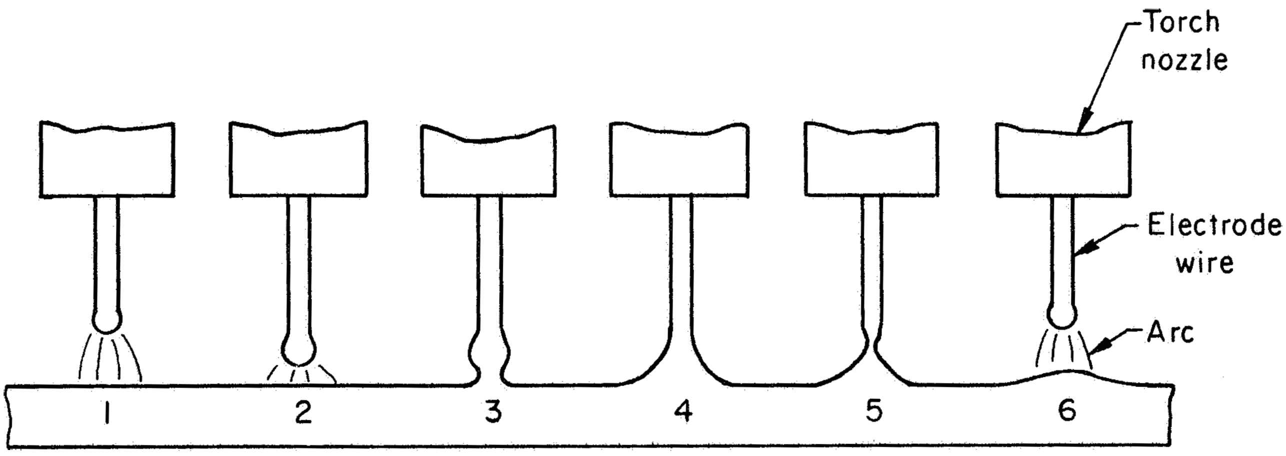


FIGURE 23. STEPS IN SHORT-CIRCUITING METAL TRANSFER

The drive rolls may be powered by an electric motor contained in the gun or by a flexible shaft leading from a motor mounted in the control unit. Some of the guns that contain the wire-drive motor also hold a small spool of filler wire. While these guns are bulkier than the other types, the number of connections to the control unit are minimized. The wire-drive mechanism also may be mounted on the control unit with the wire being driven through a flexible conduit to the welding gun. This is called "push" type of wire drive. The gun is less bulky than the pull type. Small-diameter wire may buckle when fed long distances by a pull-type mechanism. Thus, the push-type wire-drive mechanism must be placed relatively close to the welding station. The normal maximum distance that filler wire is fed is about 12 feet. One type of manual welding gun combines both a gun-located "pull" mechanism and a remote "push" mechanism for feeding the filler wire (called a "push-pull" wire feed). This equipment was especially designed for welding with very fine wires.

Automatic GMA welding guns are mounted directly to the wire-drive mechanism. The combined unit may be in a fixed location with provision for moving the workpiece underneath the nozzle or the work may be fixed and the gun-drive mechanism can be mounted on a movable head. The automatic gun contains the current pickup tube, a water-cooled jacket, and a nozzle for directing the flow of shielding gas. The automatic gun is built more ruggedly than the manual gun and is designed to operate at higher currents.

Pure argon or argon with a small addition of oxygen is the shielding gas used for spray-transfer GMA welding of stainless steel. Pure helium is not used as spray transfer is difficult to obtain, high gas-flow rates are required, and the gas shield is easier to disrupt than with the heavier argon.

When pure argon is used, the weld metal does not wet the base metal uniformly and the arc tends to wander. This can result in a nonuniform weld bead that may have undercutting at the edges of the bead. By introducing a small amount of oxygen into the argon shielding gas, the weld deposit becomes very uniform and undercutting is eliminated. Normally, argon with 1-2 percent oxygen is used for welding stainless steels. It may be necessary to raise the oxygen content to 5 percent to eliminate undercutting when welding thick stainless steel plate. The presence of oxygen in the shielding gas will cause some loss of the alloying elements in the weld metal. These metals become oxidized as the metal transfers across the arc. These losses are relatively small and ordinarily do not cause any problem. However, if the service conditions are severe, any losses of alloying elements may not be tolerated. In this case, it becomes necessary to use pure argon shielding gas even though the shape of the weld bead may not be ideal.

The shielding gas used for short-circuiting GMA welding of stainless steel is a mixture of either argon-5 percent oxygen or argon-25 percent carbon dioxide or pure carbon dioxide. Recent work has indicated that a mixture of 90 helium-7.5 argon-2.5 carbon dioxide improves wettability and bead shape (Ref. 38). Smooth arc operation is obtained with all three gases. The argon-carbon dioxide mixture and pure carbon dioxide produces a flatter and smoother weld bead. The addition of carbon dioxide to argon shielding gas also increases penetration of the weld joint which, in turn, decreases the possibility of lack of fusion in the joint (Ref. 39). Carbon may be picked up by the weld metal from the carbon dioxide mixture that will cause a decrease in the corrosion resistance of the weld metal (Refs. 39,40). This will not be a problem if the application does not require good corrosion resistance. Low-carbon 308 and 310 filler wires have been developed for use with carbon-dioxide shielding gas (Ref. 41). The low carbon content of the wire compensates for the carbon pickup from the gas. If the weld will be exposed to a corrosive atmosphere, however, the argon-oxyger shielding always should be used.

Various sizes and shapes of gas nozzles are used with GMA welding equipment. Each of these nozzles has a range of shielding gas flow rates to achieve optimum shielding. For this reason, no recommendation can be made for shielding gas flow rates for the GMA welding of stainless steels. Instead, the operator should refer to the instruction book for the equipment that is being used.

The size (diameter) of the filler wire used for spray-transfer GMA welding depends on the size of the weld bead and the penetration that is desired. As the size of the filler wire increases, the weld bead that is deposited will become thicker. Also, a higher welding current will be required to achieve spray-transfer (Ref. 42). The increase in welding current will increase penetration. The level of welding current required to achieve spray transfer for various wire sizes is shown in Table XIV.

The common sizes of filler wire used for spray-transfer GMA welding are 3/32-, 1/16-, 0.045-, and 0.035-inch diameter. The recommended sizes of filler wire for various base-metal thicknesses are shown in Table XV. Although this table includes base-metal thicknesses down to 1/8 inch, spray-transfer GMA welding usually is restricted to material with a 1/4-inch minimum thickness. The most frequently used filler wire sizes, therefore, are 1/16- and 3/32-inch diameter. Most short-circuiting GMA welding is done with 0.030-inch-diameter wire, although 0.035 and 0.045-inch diameter occasionally is used.

A "fabricated" stainless steel electrode wire is available from one electsode wire supplier (Ref. 43). This is a tubular wire containing granular alloying ingredients in the core. Extra low-carbon steel strip is roll formed into a tubular shape. At one stage in this forming operation, the premixed and pre-alloyed ingredients are metered into the partially formed tube. The tube then is tightly closed and sized by dies. During welding, the granular alloying elements mix with the low-carbon steel of the tube as it is melted by the arc to form a stainless steel weld metal. Composition of the weld metal can be easily altered by changing

TABLE XIV. APPROXIMATE WELDING CURRENT REQUIRED FOR SPRAY TRANSFER (REF. 42)

Wire Diameter, inch	Approximate Minimum Welding Current for Spray Transfer, amps
0.030	150
0.035	175
0.045	200
1/16	250
3/32	350

TABLE XV. ELECTRODE WIRE SIZE FOR SPRAY-TRANSFER GMA WELDING VARIOUS THICKNESSES OF STAINLESS STEEL

Base-metal Thickness, inch	Electrode Wire Diameter, inch
1/8	0.035 - 0.045
1/4	0.045 - 1/16
3/8	1/16 - 3/32
1/2 and thicker	3/32

the composition mix of the granular alloying elements. By using the extra-low-carbon steel strip, the carbon content of the stainless steel weld deposit can be maintained below the conventionally accepted minimum limits, It is claimed that the tolerance or alloying element content can be maintained closer than the commercial tolerances set up by the American Welding Society. This tubular wire is used in the same manner, as conventional solid wire with argon shielding gas for spray-transfer GMA welding.

Joint Design. Joint designs used for spray-transfer gas-metal-arc welding are similar to those used for shielded-metal-arc-welding, The joints are modified slightly, however, to take advantage of the greater penetration obtainable with this process. These modifications are: narrower root openings, narrower groove angle, and thicker root faces. The use of the narrower groove angle has the added advantage of requiring less filler metal to fill up the groove. For example, when a 45-degree groove angle in 314-inch-thick plate is used instead of a 60-degree groove angle, 30 percent less weld metal is required. Typical joint designs are illustrated in Figure 24.

Butt, lap, fillet, and corner joints can be welded by the short-circuiting GMA process in all positions. The penetration obtained with short-circuiting GMA welding is low, so for complete penetration, butt and corner joints in stainless steel 1/16 inch or thicker must be opened up (Figure 25). If the joint opening is too wide due to poor alignment or warped parts, the opening can be bridged with weld metal by altering welding conditions (see section on Welding Procedures). A copper backup bar can be used when making butt welds to control excess penetration or burnthrough. However, the backup bar is not as important here as with other types of arc welding since these problems are not as apt to occur with short-circuiting GMA welding.

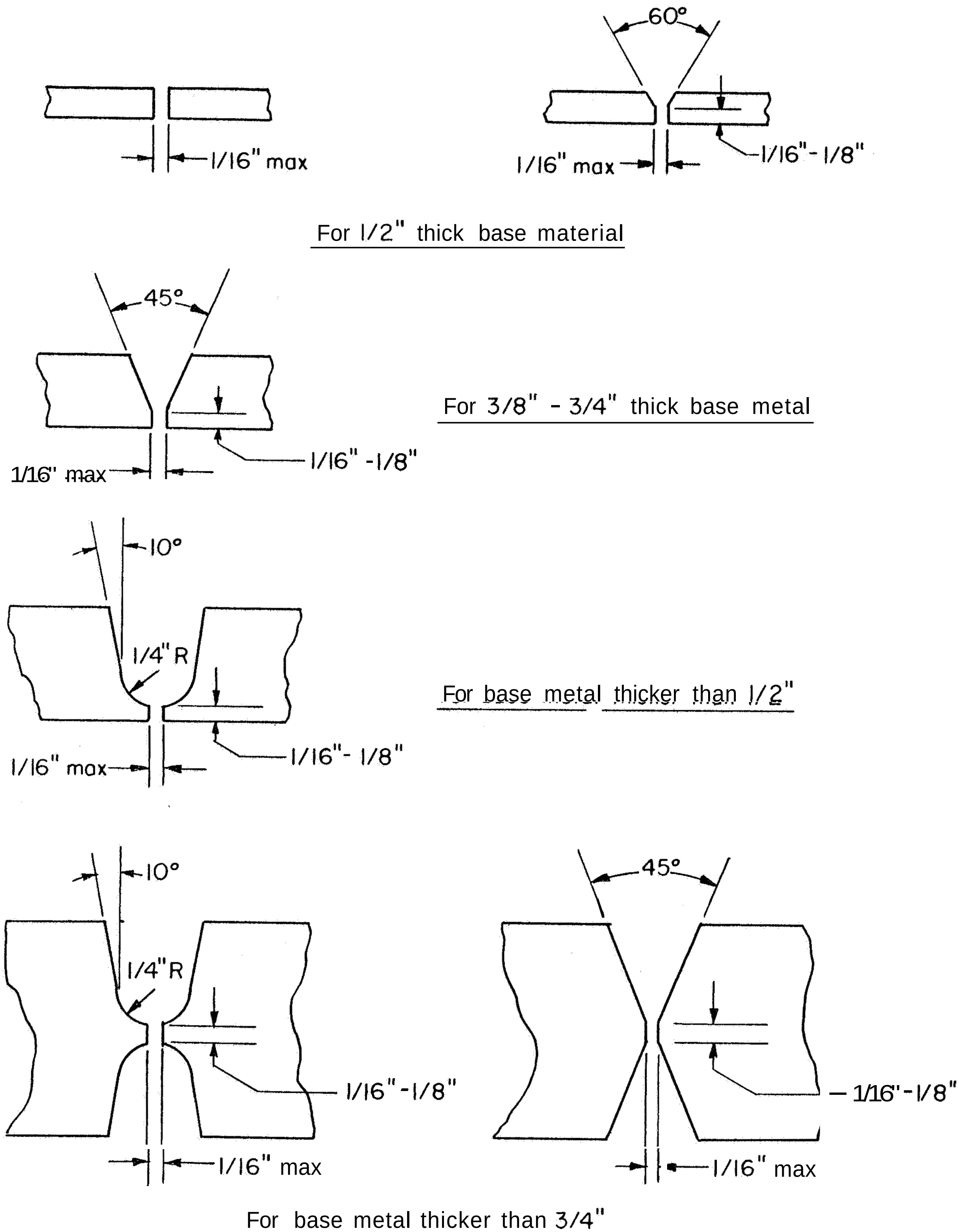
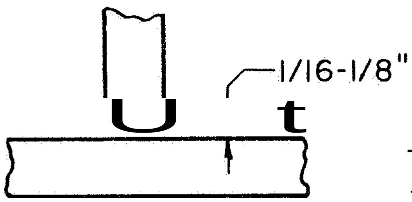
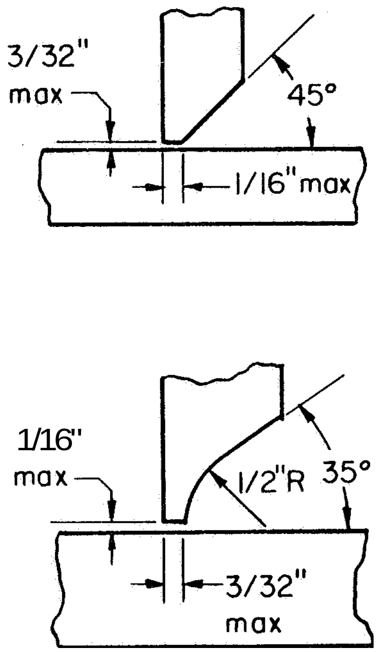


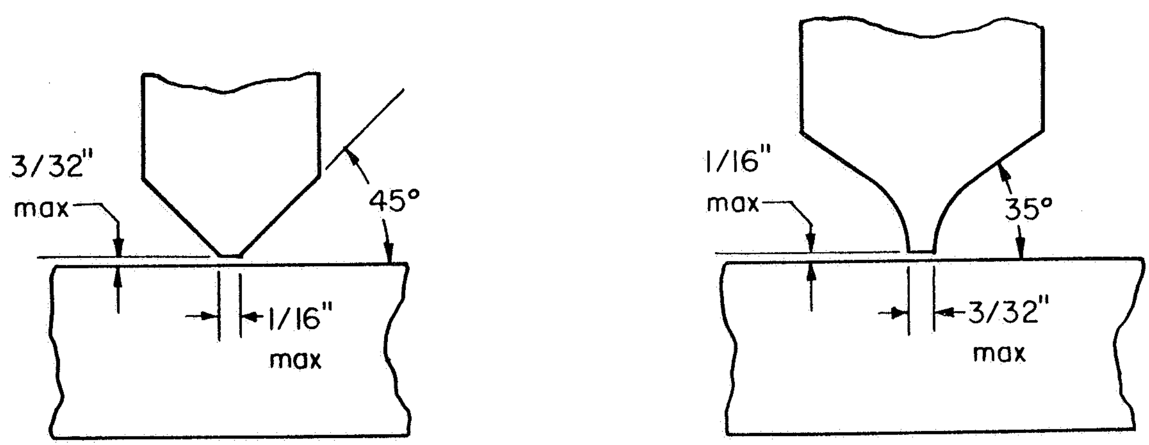
FIGURE 24. TYPICAL JOINT DESIGNS FOR GAS-SHIELDED METAL-ARC WELDING OF STAINLESS STEEL



For 1/4" thick base material welded from both sides



For 1/4"- 3/4" thick base material



For 3/4" and thicker base material

FIGURE 24. (Continued)

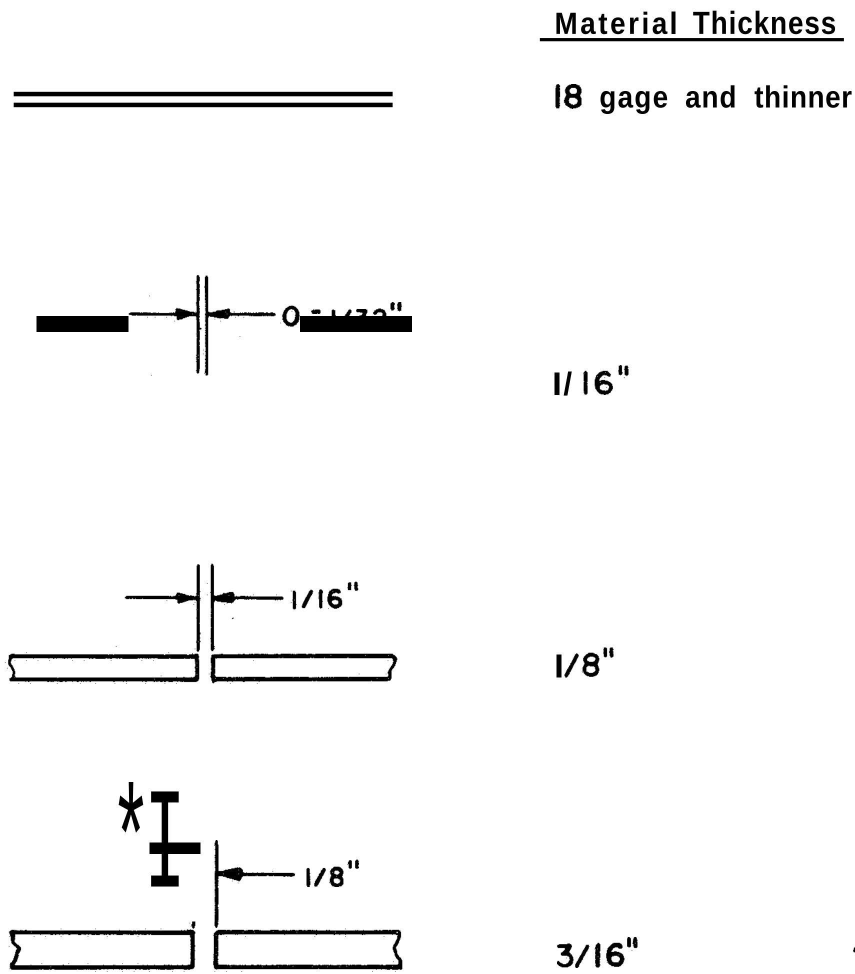


FIGURE 25. TYPICAL BUTT JOINTS FOR SHORT-CIRCUITING GMA WELDING OF STAINLESS STEEL (Ref. 41)

Welding Procedures. Gas-metal-arc welding of stainless steel may be 'done either automatically or manually (semi-automatic). Manual welding is similar to shielded metal-arc welding in that the operator holds and manipulates the *welding torch or gun. Less operator skill is required, though, since constant arc length is maintained automatically and there is no need to move the gun to compensate for electrode melting. For automatic welding, the operator's duties consist of setting the welding conditions, aligning the gun with the joint, and starting and stopping the welding operation. During welding, the operator should watch the operation carefully to be sure that the proper gun alignment is being maintained and that welding is progressing properly.

Typical welding conditions for spray-transfer and short-circuiting GMA welding of stainless steel are given in Table XVI.

Weld joint penetration, weld bead reinforcement, and bead shape can be altered by adjusting certain welding conditions. Penetration and bead width both increase as the welding current increases. A short arc will "dig in" and increase penetration, while if less penetration is desired, a longer arc should be used. A higher welding current also will produce a heavier weld deposit. The amount of electrode "stick-out" will affect the rate of melting of the wire. (Stick-out is the distance from the end of the contact tube to the end of the electrode wire.) The greater the stick-out, the higher will be the melting rate (Ref. 42). By changing the amount of stick-out, the amount of filler wire that is melted and the size of the weld bead can be altered without changing the welding current. The amount of stick-out also influences the amount of penetration that is obtained. As the stickout increases, penetration decreases, In manual welding, the operator can take advantage of this behavior. If the joint has poor fitup with a wide root opening, stick-out should be increased to decrease penetration and make the weld metal freeze faster. By using a slight weave in conjunction with the increased stick-out, the operator can bridge the wide joint spacing without burning through the joint.

TABLE XVI. TYPICAL WELDING CONDITIONS FOR GMA WELDING OF STAINLESS STEEL (REF. 10)

Wire Diameter, inch	Welding Current, amps	Arc Voltage, volts	Wire Feed Speed, ipm	Metal Deposition Rate, lb. per hour
		Spray Transfer		
1/16	210	23	132	7.0
	260	24	168	8.8
	300	25	200	10.6
3/32	300	24	60	8.3
	400	25	95	11.8
	500	27	125	15.2
		Short Circuiting		
0.030	50-150(flat)	18-24		
	50-125(vertical or overhead)	18-24		
0.035	75-175(flat)	18-24		
	75-150(vertical or overhead)	18-24		
0.045	100-225(flat)	18-24		
	100-175(vertical or overhead)	18-24		

Increasing the welding speed will decrease both penetration and bead width. If the speed becomes too fast, undercut will occur along the edges of the bead and there may be areas of lack of fusion. Higher travel speeds can be used when the weld is being deposited in narrow grooves in thin material than when welding wide joints in thick plate.

In manual GMA welding, the operator holds and manipulates the welding gun. The important thing for the operator to remember is that the motion of the gun along the joint must be uniform and the position of the gun with respect to the joint must be held constant.

In shielded metal-arc welding, penetration is relatively shallow and variations in the movement of the electrode along the joint do not affect penetration very much. In GMA welding, penetration is much greater and changes in travel speed can have a greater effect on penetration. This can lead to burnthrough of the joint or lack of penetration if the operator moves the torch erratically along the joint. Motion must be as uniform as possible.

Changing the angle of the welding gun will change the shape of the weld bead. Tilting the gun in the direction of welding (backhand technique) decreases penetration, increases bead width, and improves the smoothness and contour of the bead surface. Cap passes on multipass welds may be made with the backhand technique. With the gun tilted back away from the direction of welding (forehand technique), penetration, though greater than with the backhand technique, still is not as much as when the gun is perpendicular to the bead surface. Automatic welds normally are made with the gun perpendicular or with a small amount of backhand tilt.

The same precautions should be exercised in protecting the underside of the weld joint in GMA welding as in GTA welding. Grooved copper backup strips and inert-gas backing may also be used in GMA welding. In making multipass welds, maximum quality is obtained by grinding out the underside of the root pass and rewelding from that side. Root passes are subject to various defects such as incomplete penetration and lack of fusion. By grinding out the root pass to sound metal and rewelding, these defects can be eliminated from the finished joint.

Precautions. The precautions to be observed in GMA welding of stainless steels are concerned with both the equipment and welding procedure.

Equipment Precautions. Successful GMA welding depends on feeding the electrode wire through the gun at a precise and uniform speed. This means that the equipment must be kept in good operating condition. Most problems with GMA welding equipment may be traced to a wire feeding system that has not been kept clean and in good condition. A well-kept schedule of preventive maintenance of this system plays a major role in successful GMA welding. Important points to check in such a schedule are:

(1) Adjustment of wire-straightening rolls (if so equipped). Improper adjustment can cause the wire to bend as it exits from the contact tube and the arc will not be properly positioned in the weld joint.

(2) Alignment of the wire with the groove in the feed rolls. Misalignment will cause bending of the wire. The wire also may climb out of the groove with resulting erratic wire feeding.

(3) Feed roll clamping pressure. If thepressure is too light, slippage and erratic feeding will result. If the pressure is too heavy, the wire may be deformed to the point where it will not pass freely through the contact tube.

(4) The wire-feed cable between the wire reel and rhe feed rolls should be clean and free of kinks. Dirt in the cable can be transferred to the wire and ultimately to the weld metal. A buildup of dirt in the cable and kinks in the cable can restrict free movement of the wire through the cable. As a result, wire feed may become erratic.

(5) The sizes of the wire feed cable, feed rolls, and contact tube should match the size of the electrode wire being used. If any of these parts are of the improper size, the wire will not feed smoothly. If the contact tube is too large, poor pickup of the current will occur, The equipment manufacturers suggestions should be followed regarding proper sizes of these parts.

(6) Distance between wire feed rolls and contact tube or wire feed cable. This distance should be as short as possible. In this area, the wire is unsupported and if this distance is large, the wire may buckle.

(7) Winding of the electrode wire on the spool or coil. If the wire becomes loose on the spool or coil as it feeds, loops of wire may become entangled stopping feeding of the wire. Most mounting spindles for wire spools or coils are equipped with friction devices that apply a small amount of tension to the wire as it feeds. This prevents loosening of the wire. Care should be taken when mounting the wire spool or coil that entanglement of the wire does not occur.

The operator should check the gas passages and gas-shielding nozzle periodically to be sure that the flow of shielding gas is not being disrupted. Spatter tends to build up on the inside of the nozzle. If this buildup becomes too great, proper shielding cannot be obtained. Thus, the inside of the nozzle should be cleaned periodically.

Contact tubes may be another source of trouble. Contact tubes are made from copper or copper alloy and being softer than the welding wire, tend to wear from the passage of the wire through the tube. This enlarges the base of the tube, which, in turn, can cause erratic current pickup. Contact tubes should be replaced periodically to maintain good current before wear becomes so great that problems occur.

Procedure Precautions. The quality of the weld joint also depends on the welding procedures that are used. Slight variations in procedure can have major effects on the quality of GMA joints in stainless steels. The most frequently encountered defects and their causes are discussed in the following paragraphs.

Burnthrough and excessive penetration can be caused by putting too much welding heat into the joint. The welding current should be decreased or the travel speed increased. Penetration will be decreased by tilting the gun toward the direction of welding (forehand technique). This defect also may be caused by excessive root opening or too small a root face. If the joint dimensions cannot be changed, the use of a copper backup bar or a weaving technique can help to prevent burnthrough.

Lack of penetration is caused by the opposite conditions to those that cause excessive penetration. The welding current may be too low or the travel speed too high. The gun may be at too large an angle with the weld joint (either backhand or forehand). Straightening up the gun angle will increase penetration. Increased root opening may be needed. The position of the arc in the weld puddle also will affect penetration. The closer the arc is to the front of the puddle, the greater will be the amount of penetration.

Overlap occurs when the weld metal does not fuse to the base metal at the edges of the top surface of the joint. Usually, it is caused by carrying a weld puddle that is too large. Reducing the wire-feed speed or increasing the travel speed will help to correct this problem. Another solution is to use a slight weave so that the arc will cover all areas of the weld joint where fusion is desired. Keeping the arc at the front of the puddle will improve fusion and reduce overlap.

An unfilled groove along the edge of the weld bead is called undercut. Decreasing the travel speed will help to fill up these grooves. The use of an argon-oxygen shielding-gas mixture will reduce undercut.

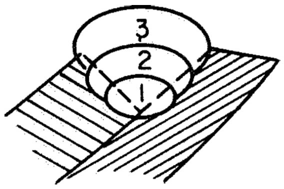
"Wagon tracks" may occur in multipass welding. It is the name given to a line of voids that are trapped at the edges of the underlying bead when the subsequent bead is deposited. This defect only shows up on an X-ray photograph of the joint when the line of voids has the appearance of wagon tracks on a dirt road. Wagon tracks can occur if the lower weld bead is too high crowned. The use of argon-oxygen shielding gas will improve the shape of the weld bead surface. Bead shape also can be altered by adjusting the arc voltage and travel speed. Care should be used when depositing the second pass to be sure that the arc melts the entire surface of the underlying bead.

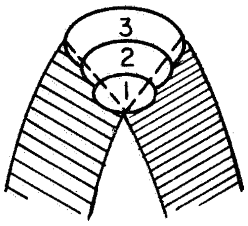
Applications. Short-circuiting GMA welding has been used to fabricate a 54-inch-long turbine bucket blade of Type 410 stainless steel (Ref. 38). Two pieces of stainless steel 0.030 inch thick were welded together to form a hollow blade. The weld along the leading edge of the blade was a "nose" weld while the trailing edge weld was a lap weld. The welding conditions are given in Table XVII. The first pass was made without oscillation while the second and third passes used some oscillation. The joints were preheated to 700 F. The shielding gas was 90 percent helium-7.5 percent argon-2.5 percent carbon dioxide.

Submerged-Arc Welding. Submerged-arc welding can be used with all classes of stainless steels. However, filler wires and fluxes are available for welding only the common types of stainless steels. Chromium-nickel stainless steels that are fully austenitic or that are intended for prolonged high-temperature service seldom are submerged-arc welded for metallurgical reasons.

Submerged-arc welding is characterized by deep penetration and high rates of weld-metal deposition. This is because the flux acts as an insulator to keep the welding heat concentrated in a relatively small area. The deep penetration that is obtained makes it possible to weld thick plates with only a few passes. The high weld-metal deposition rates are possible because high welding currents can be used. The flux controls the high-current arc more effectively than does the gaseous shield used with other arc-welding processes. As a result of the

TABLE XVII. WELDING CONDITIONS FOR SHORT-CIRCUITING GMA WELDED TYPE 410 STAINLESS STEEL TURBINE BLADE (Ref. 38)





Pass No.	Current, amp	Voltage, volts	Travel Speed, ipm	Bead Width, in.
LAP WELD				
1	135	23	16	1/4
2	125	23.5	9.5	7/16
3	135	23	4.5	3/4
NOSE WELD				
1	135	23	16	1/4
2	125	23.5	9.5	7/16
3	125	24	7	9/16

high-deposition rate, welding can be done more rapidly than by GMA, GTA, or shielded metal arc. The combination of deep penetration and high welding speed 'makes submerged-arc welding a very economical welding process.

Submerged-arc welding is limited to the flat or horizontal position, It cannot be used to weld material thinner than about 1/2 inch due to its deep penetration. This deep penetration also makes it necessary to back up single-pass welds or root passes in multipass welds with a copper or flux backup to prevent burnthrough. It is difficult to track the joint since the end of the electrode and the arc are buried under the flux and cannot be seen by the operator.

In the welding of stainless steel, slow cooling promotes segregation of the alloying elements in the weld metal. This means that some areas of the weld metal may not contain any ferrite. Microcracking or fissuring can occur in such areas decreasing the overall ductility and impact strength of the weld metal. To eliminate this problem, the overall composition of the weld metal must be adjusted to provide a total ferrite content somewhat higher than required for other arc-welding processes. Since the ferrite content of submerged-arc welds must be relatively high, the danger of forming the brittle sigma phase at high service temperatures is increased (Ref. 10,33). Thus, submerged-arc welding is seldom used if high-temperature service is anticipated. The impact strength and ductility also will suffer as a result of the large grain size of the weld metal and heat-affected zone. Again, this is caused by the slow cooling rates.

Another disadvantage caused by slow cooling of submerged-arc welds is that it caused sensitization or loss of corrosion resistance of the weld and heat-affected zone. If the corrosion resistance of the finished part is of importance, then it is necessary *to* use a low carbon or one of the stabilized types of stainless steel.

Submerged-arc welds tend to pick up silicon from the flux due to reactions between the flux and the weld metal as metal transfers from the electrode wire to the weld puddle (Ref. 10,33). High silicon content also will cause fissuring which reduces the impact strength of welds in chromium-nickel stainless steels.

Equipment. The choice of power supply depends largely on the work to be welded. D-C permits fast arc starting, gives good control of the weld bead shape, and provides quick current buildup at the start of the weld which is advantageous if short welds are being made. Best control of the bead shape and deepest penetration are obtained with D-C reverse polarity (electrode positive), while the highest welding speeds and shallowest penetration are obtained with D-C straight polarity (electrode negative). The use of A-C current provides a degree of penetration in between that of D-C straight and D-C reverse polarity. A-C current also cuts down on arc blow (the swerving of the arc from its normal path due to magnetic forces) which can become a severe problem when very high welding currents are used.

The selection of the filler wire and flux should go hand-in-hand. If an alloy filler wire is to be used, the flux should be neutral. If the alloying elements are to be added from the flux (an alloy flux), then a mild steel filler wire is used. Filler-wire-flux combinations have been developed for welding the common types of stainless steels (304, 308, 309, 316, 347, 410, and 430). Since the problem of fissuring can become serious when welding stainless steels, the supplier should always be consulted so that the filler wire and flux can be matched to the composition of the stainless steel base metal that is to be welded.

The choice of filler wire or flux composition also will depend on the amount: of dilution that is expected of the weld metal by melted base metal. Dilution is of more concern in submerged-arc welding than in other types of arc welding due to the greater penetration that is obtained. Dilution can vary all the way from 10 percent to 75 percent depending on the design of the joint, Fluxes are available that are specifically designed for high-dilution welding (Ref. 44). Again, the supplier should be consulted so that the proper composition can be selected for the particular joint that is to be welded.

The size of filler wire used will depend on the range of welding current to be used. Typical current ranges for different sizes of wire are shown in Table XVIII.

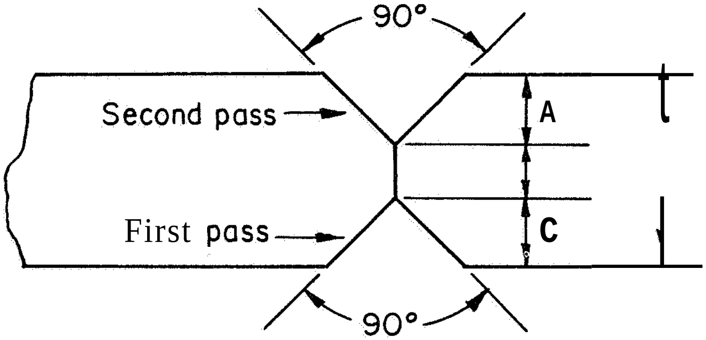
The welding flux is available in different particle sizes. The size that is used will depend on the current used and the composition of the flux. The manufacturer's recommendations should be followed when selecting the flux particle size.

Joint Design. Typical butt and fillet joints are shown in Figure 26. The distinguishing feature of joints prepared for submerged-arc welding is the thick root face. The thick face is required to accomodate the deep penetration without burnthrough. Sometimes, a thinner root face is used and the root pass is deposited by shielded metal-arc welding with the joint being completed by submerged-arc welding. Some operators feel that better control of penetration is obtained using this technique. A large number of different joint designs are presented in the Welding Handbook, Fifth Edition, Chapter 28. Most of these apply to carbon steel, but can also be used with stainless steel if a faster travel speed is used to compensate for the higher deposition rate of stainless steels.

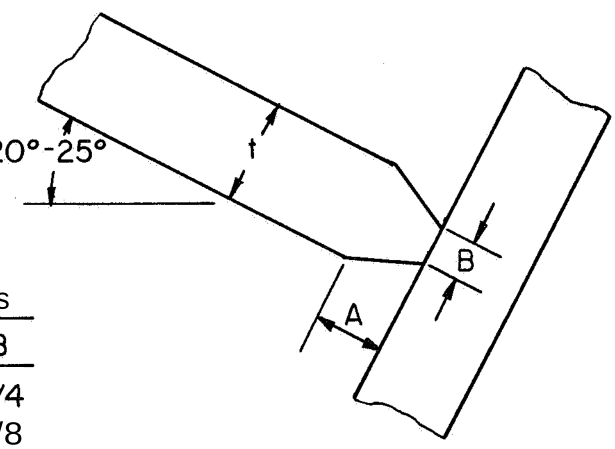
Welding Procedures. Special steps should be taken to prevent burn-through when making single-pass welds or the root pass in multipass welds. This is because of the deep penetration characteristic with this process. Two methods have already been mentioned in the section of joint design. These were to use thick root faces or to make the root pass by shielded metal-arc welding. (Figure 27). Other techniques include the use of gooved-copper backup strips, a pad of flux supported against the joint underside by inflated firehose, or a stainless steel backing strip.

TABLE XVIII. CURRENT RANGES FOR VARIOUS SIZES OF SUBMERGED-ARC ELECTRODE WIRE (REF. 29)

Wire Diameter, inch	Current Range, amps
3/32	120-700
1/8	220-1100
5/32	340-1200
3/16	400-1300
1/4	600-1600



Dimensions, inches			
t	A	B	C
1/2	1/8	1/4	1/8
5/8	3/16	1/4	3/16
3/4	1/4	1/4	1/4
7/8	5/16	5/16	1/4



Dimension, inches		
t	A	B
5/8	3/8	1/4
3/4	1/2	3/8
1	5/8	7/16
1-1/4	3/4	7/16
1-1/2	7/8	7/16

FIGURE 26. TYPICAL WELD JOINTS FOR SUBMERGED-ARC WELDING OF STAINLESS STEEL (Ref. 45)

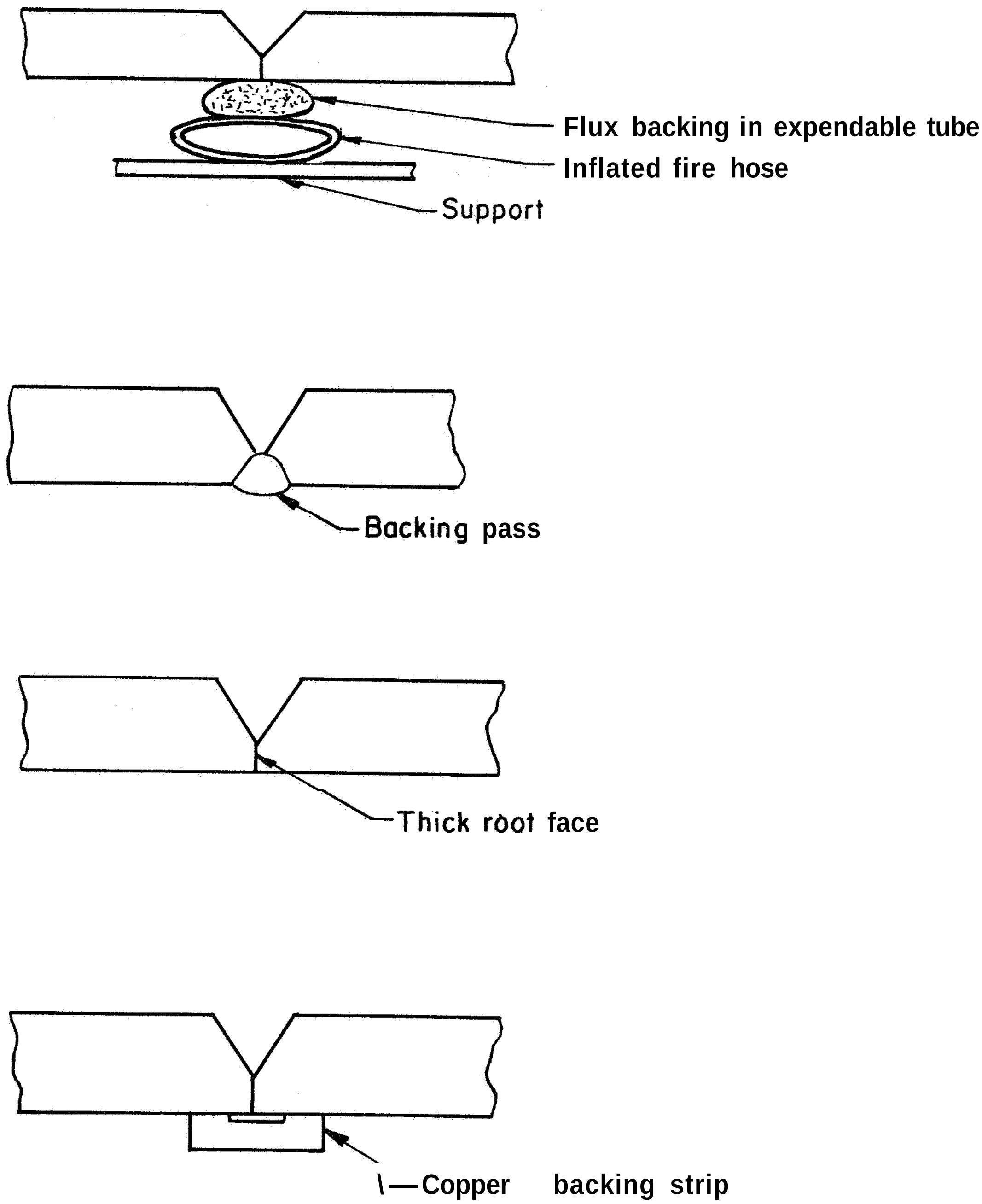


FIGURE 27. METHODS OF BACKING THE JOINT IN SUBMERGED-ARC WELDING TO PREVENT BURNTHROUGH

Starting the arc is more difficult in submerged-arc welding than in GMA welding since the flux can prevent contact of the electrode with the work. The methods most frequently used are as follows:

(1) Fuse-ball start. Place a small, tightly rolled ball of steel wool between the electrode and the work. The electrode is lowered until the ball is compressed to about half its size. Flux is then applied and the welding current is turned on.

(2) Pointed-wire. The end of the electrode is trimmed to a point with bolt cutters. The electrode is lowered until it just touches the work. After flux is applied, the current is turned on.

(3) Scratch-start. The electrode is lowered until it touches the work and flux is applied. Travel of the gun along the joint is started and then the current is turned on.

(4) Retract start. This method is used with control systems that have provision for retract starting. The electrode is lowered until it touches the work and then flux is applied. When the current is turned on, the electrode retracts, starting the arc.

(5) High-frequency. This type of starting requires a special high-frequency starting equipment attached to the welding circuit. Flux is applied to the joint. When the current is turned on, the electrode moves toward the work. When the end of the electrode is about 1/16 inch away from the work, a high-frequency spark will jump from the electrode to the work. The welding arc then will be established along this spark path.

The welding conditions that are used are similar to those that would be used for welding mild steel. The chief exception is that the current for welding stainless steel is about 80 percent of that used for welding mild steel. Typical conditions are given in Table XIX for the butt joints illustrated in Figure 26.

TABLE XIX. CONDITIONS FOR SUBMERGED-ARC WELDING BUTT JOINTS OF FIGURE 26 (REF. 45)

	Finishing Weld				Backing Weld			
Thickness in.	Current, Amps	Voltage, Volts	Speed, ipm	Wire Dia, in	Current, Amps	Voltage, Volts	Speed, ipm	Wire Dia, in
2/8	575	32	24	3/16	525	30	20	3/16
1/2	900	33	18	3/16	700	35	18	3/16
5/8	900	35	12	1/4	700	33	16	3/16
3/4	950	35	12	1/4	700	33	15	1/4
7/8	1025	35	12	1/4	715	33	15	1/4

Most submerged-arc welding is done in the flat position. Since the molten weld puddle is large, only small inclinations of the work from the flat position can be tolerated without causing pronounced changes in the bead shape. If welding is done in a slightly up-hill position, the bead will be narrow and highly crowned. If the part is tipped so welding is done down-hill, the bead will be broad with a depression in its center. The limits on plate inclination are about 6 degrees if the welding current is below 800 amperes. At higher currents, even less tipping can be tolerated. If the part is tipped laterally, the bead will have a hump on the down-hill side. Maximum lateral tippage should be no more than 3 degrees. (Ref. 45).

When girth welds are made in cylindrical parts, the arc is offset a short distance from the top-center position if welding is being done from the outside, or the bottom-center position if welding is being done from the inside. This is done so that the weld has a chance to solidify before the slope becomes too great.

Electron-Beam Welding. Electron-beam welding can be a very attractive process for welding stainless steel parts. The process can be used for welding material with thicknesses ranging from the foil gages to over 2 inches in a single pass. In addition to being very versatile regarding material thickness that can be welded, electron-beam welding has two other major advantages: (1) welding is done in a vacuum and (2) very narrow welds are produced. By welding in a vacuum, contamination from gaseous impurities is virtually non-existent. The vacuum atmosphere is even purer than the inert-gas atmosphere of GTA or GMA welding. The very narrow welds that are produced are subject to very little distortion or warpage.

The requirement for welding in a vacuum is also one of the chief disadvantages of electron-beam welding. All the parts being welded must be placed in a vacuum chamber. The chamber size thus limits the size and shape of the parts being welded. Movement of the parts during welding and observation of the welding operation also are hindered by the vacuum chamber. Loading and unloading parts from the chamber and pumping the vacuum on the chamber after each loading operation is time consuming. As a result, production rates for electron-beam welding are quite low. Sliding vacuum chambers have been developed to alleviate this problem and work currently is under way to develop "out-of-vacuum" electron-beam welding.

The other major disadvantage of electron-beam welding is the cost of the equipment. Electron-beam welding equipment is expensive. Unless the special characteristics of electron-beam welding are required, it is cheaper and usually quicker and easier to use one of the more conventional welding processes.

Electron-beam welding equipment is classed as eitherhigh-power density or low-power density. Only the high-power-density equipment is capable of producing deep narrow welds. Low-power-density equipment was produced in the early days of electron-beam welding development, but as far as is known, no low-power-density equipment is being produced currently. However, such equipment still exists and may be used occasionally by some fabricators.

High-power-density equipment may be further subdivided into low-voltage and high-voltage classes. In low-voltage equipment, the high welding power is achieved by using a "low" accelerating voltage and high beam currents. Maximum voltage obtainable on such equipment normally is around 30 kv although some 60 kv equipment is now being produced. The 60 kv equipment really should be classed as medium-voltage equipment. The high-voltage equipment uses accelerating voltages as 'nigh as 150 kv in conjunction with low-beam currents.

There are advantages and disadvantages to both high- and low-voltage electron-beam welding. The process that is used depends on the needs of the particular fabricator. An almost equal number of high- and low-voltage welders have been produced and are in use in the United States (Ref. 46).

In general, higher power can be achieved with the low- and medium-voltage equipment. Most equipment of these classes have power ratings in the range of 9 to 15 kw, although a 60 kw medium-voltage welder has been produced (Ref. 47).

The high-voltage welders usually have power ratings in the 3 to 6 kw range. The results obtainable with both the high- and low-voltage high-power-density welders are comparable. Weld joint shape produced by both classes is comparable. The low-voltage welders have slightly greater penetrating ability due to their generally higher power ratings. The 60 kw welder is claimed to be capable of penetrating 9-inch aluminum plate in a single pass. The high-voltage welders generally are better suited for welding thin material and small parts. This is because the beam can be accurately focused to a smaller diameter than the low-voltage beam. High-voltage welders are equipped with optical viewing devices that enable the operator co observe the welding operation. The high-voltage electron beam has a greater depth-of-focus than a low-voltage beam. This means that the part can be located further from the gun, up to 24 inches away. In low-voltage welding, the part must be about 3 to 6 inches from the gun. However, recent advances in equipment design permit parts to be welded at greater distances from the gun. Changes in shape of the part do not affect the welding operation in high-voltage welding while the beam must be refocused when welding variable shape parts in low-voltage welding.

Welding Procedures. Welding Procedures used in electron-beam welding are dependent on material thickness and the type of electron gun being used. For a given thickness of material, various combinations of accelerating voltage, beam current, and travel speed are satisfactory. In electron-beam welding, the electrical parameters do not adequately describe the heat-input characteristics of the beam since these characteristics are affected significantly by the focus of the beam. Measurements of beam diameter are difficult to make under production conditions so that the transfer of welding parameters between different equipment units is very difficult. Fortunately, suitable welding parameters can generally be developed on a given piece of equipment with only a very few trials.

In very thick material, the first pass made to completely penetrate the joint sometimes is undercut along both edges of the weld metal. This undercutting can be eliminated by a second weld pass made at somewhat lower energy levels with a slightly defocused beam, However, undercutting frequently can be reduced by making minor adjustments in travel rate. The underside of electron-beam welds also may exhibit an undesirable contour. Some type of metal-removal operation is generally required to produce an acceptable underside contour.

The flat welding position usually is used in electron-beam welding. The welding positions that can be used are limited by the versatility of the available welding equipment. Table XX shows some of the welding conditions that have been used in the electron-beam welding of stainless steels.

Applications. Aerojet-General Corporation used low-voltage electron-beam welding to fabricate spherical pressure vessels from Type 410 stainless steel (Ref. 48). These spheres were made of two hemispheres electron-beam welded together. The spheres were about 12 inches in diameter with 0.080-inch-thick wall. The hemispheres were heat treated prior to welding. Burst testing of the as-welded spheres indicated that failures initiated in the base metal well away from the weld joint.

Electron-beam welding has been used to fabricate a variety of honeycomb structures (Ref. 46,49). Electron-beam welding is well suited for this application as the close control of welding parameters needed for welding thin sheet is readily obtained. A typical panel is shown in Figure 28. The core structure is made from thin stainless steel sheet formed to a sine wave configuration. The cover sheets are electron-beam welded to the nodes of the core sheet by the burn-through technique.

TABLE XX. TYPICAL ELECTRON-BEAM WELDING CONDITIONS FOR STAINLESS STEEL

Material	Thickness, inch	Beam Voltage, kv	Beam Current, ma	Travel Speed, ipm	Reference
304	0.5	30	125	30	50
304	0.5	30	130	30	50
304	0.5	30	100	20	50
304	0.25	25	85	22	50
304	0.062	16	30	20	50
304	0.0185	12	22	70	50
304	0.125	23	50	22	50
304	2	30	500	10	51
18-8	0.1	100	10	80	52
18-8	0.2	150	10	90	52
18-8	0.8	150	10	6	52
304	0.049	140	20.0	494	52
304L	0.5	150	17.5	34	52

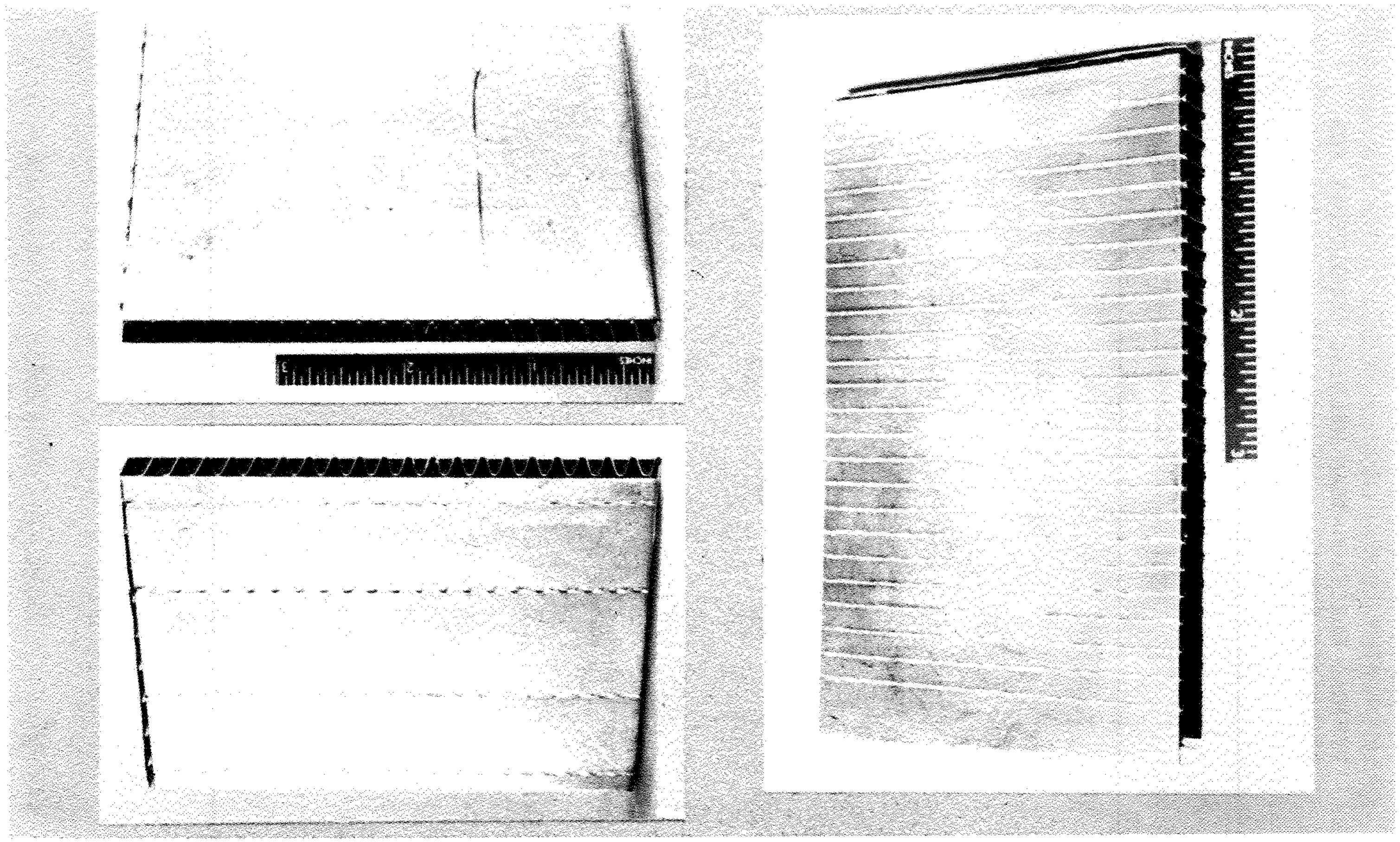


FIGURE 28. STAINLESS STEEL HONEYCOMB PANEL FABRICATED BY ELECTRON-BEAM WELDING
(Courtesy Hamilton-Standard Division, United Aircraft Corporation)

Another application, illustrated in Figure 29, is a stainless steel filter assembly (Ref. 46,49). A ribbed, porous filter body has been electron-beam welded to solid stainless steel end flanges.

Resistance Spot Welding. All of the heat required to accomplish joining by resistance spot welding is supplied by the passage of an electric current between two opposing electrode tips that contact the surfaces of the parts to be joined. This resistance heating melts a localized volume of metal at the sheet-to-sheet interface region. The molten nugget of metal solidifies to form the weld.

All three classes of stainless steel can be resistance spot welded. The austenitic chromium-nickel stainless are especially easy to spot weld with the welds being tough and ductile. Since spot welds cool at a rapid rate, the loss of corrosion resistance by slow cooling is minimized. Spot welds in the ferritic chromium stainless steels have a tendency to be brittle. Thus, if good joint ductility is required, spot welding of the ferritic stainless steels is not recommended. Special techniques are required for spot welding the hardenable chromium stainless steels. Spot welds in these steels harden on cooling and are very hard and brittle. Welds in these steels must be tempered after welding to reduce brittleness by heating the parts in a furnace or giving the welds a second pulse of current immediately after the weld cools.

Spot welding can be used only to make lap joints. The maximum thickness of stainless steel that can be welded is about 3/8 inch. The spot welded joint is not leaktight and may have poor fatigue strength. Since spot welds cool rapidly, there is little problem with loss of corrosion resistance due to slow cooling. However, the spot-welded joint has a built-in crevice surrounding each individual weld that may cause the joint to corrode rapidly in certain corrosive environments.

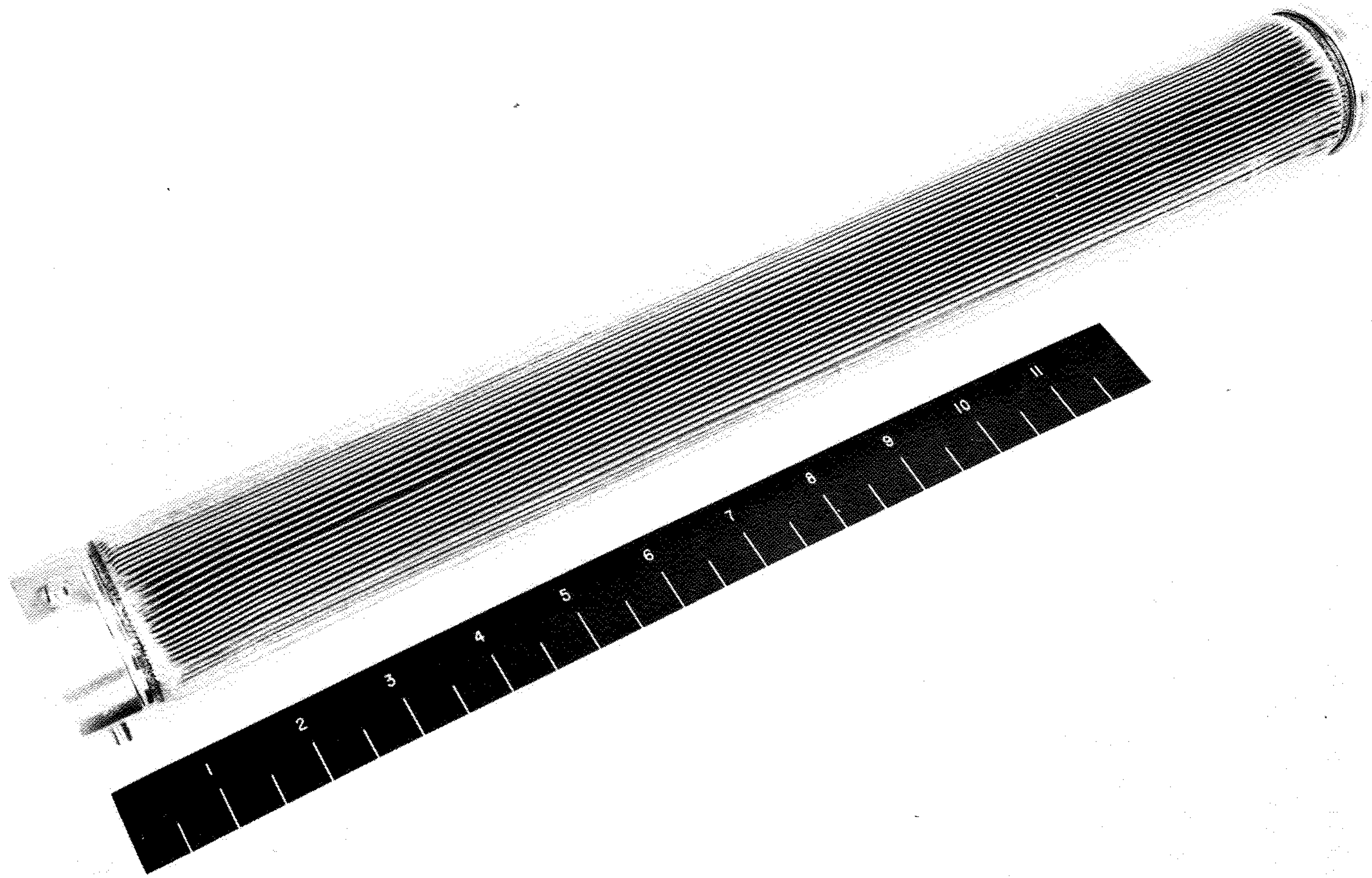


FIGURE 29. ELECTRON-BEAM WELDED STAINLESS STEEL FILTER ASSEMBLY
(Courtesy Hamilton-Standard Division, United Aircraft Corporation)

Equipment. Stainless steels are welded using conventional resistance sppt-welding equipment. Spot welding equipment normally provides accurate control over the basic spot-welding parameters: weld current, weld time, and electrode force. Each of these parameters may vary to a certain degree without appreciably reducing weld quality. It is, however, desirable to have enough control over the parameters to obtain reproducible results, once the optimum settings are obtained for a given application. Because of the higher electrode forces required for welding stainless steel, the larger press-type machines are preferred.

RWMA Class 2 or 3 electrodes usually are used for spot welding stainless steel. However, if very high pressures or high electrode temperatures are anticipated, a Class 11 electrode should be used. Internal water cooling is recommended to improve tip life. Both flat face and spherical radius tip geometries are used.

Welding Procedures. In general, the spot welding of chromium-nickel stainless steel is similar to that of carbon steel. However, some changes in welding conditions are required to compensate for the different thermal and electrical characteristics of stainless steel. Recommended conditions are given in Table XXI.

The minimum sheet overlap given in the table of conditions insures a flat, uniform contract between the two sheets. If the overlap is less, the sheets may not contact each other evenly at the spot where welding is to take place, causing poor welds. When a series of spot welds is being made, some of the welding current will be shunted through the previously made welds. This shunting reduces the amount of current available to make the weld. If the minimum joint spacing is followed, shunting of the current will not become a problem.

The current required for spot welding stainless steel is lower than that used for carbon steel, due to the higher electrical resistance of stainless steel. Also,

TABLE XXI. RECOMMENDED CONDITIONS FOR RESISTANCE SPOT WELDING STAINLESS STEELS (REF. 53)

THICKNESS "T" OF THINNEST OUTSIDE PIECE (SEE PAR. 101 AND NOTES 1,2,3 AND 4 BELOW)	ELECTRODE DIAMETER AND SHAPE (SEE PAR. 102 AND NOTE 5)		NET ELECTRODE FORCE (SEE PAR. 103)	WELD TIME (SINGLE IMPULSE) (SEE PAR. 104)	WELDING CURRENT (APPROX.) (SEE PAR. 106) AMPS.		MINIMUM CONTACTING OVERLAP (SEE PAR. 109)	MINIMUM WELD SPACING (SEE PAR. 108 AND NOTE 6 BELOW) ₵ TO ₵	DIAMETER OF FUSED ZONE (SEE PAR. 107)	MINIMUM SHEAR STRENGTH (SEE PAR. 105) LB. ULTIMATE TENSILE STRENGTH OF METAL			THICKNESS "T" OF THINNEST OUTSIDE PIECE (SEE PAR. 101 AND NOTES 1,2,3 AND 4 BELOW)
INCHES	D, IN., MIN.	d, IN., MAX.	LB.	CYCLES (60 PER SEC.)	TENSILE STRENGTH BELOW 150000 PSI	TENSILE STRENGTH 150000 PSI AND HIGHER	IN.	IN.	IN., APPROX.	70000 UP TO 90000 PSI	90000 UP TO 150000 PSI	150000 PSI AND HIGHER	INCHES
0.006	3/16	3/32	180	2	2000	2000	3/16	3/16	0.045	60	70	85	0.006
0.008	3/16	3/32	200	3	2000	2000	3/16	3/16	0.055	100	130	145	0.008
0.010	3/16	1/8	230	3	2000	2000	3/16	3/16	0.065	150	170	210	0.010
0.012	1/4	1/8	260	3	2100	2000	1/4	1/4	0.076	185	210	250	0.012
0.014	1/4	1/8	300	4	2500	2200	1/4	1/4	0.082	240	250	320	0.014
0.016	1/4	1/8	330	4	3000	2500	1/4	5/16	0.088	280	300	380	0.016
0.018	1/4	1/8	380	4	3500	2800	1/4	5/16	0.093	320	360	470	0.018
0.021	1/4	5/32	400	4	4000	3200	5/16	5/16	0.100	370	470	500	0.021
0.025	3/8	5/32	520	5	5000	4100	3/8	7/16	0.120	500	600	680	0.025
0.031	3/8	3/16	650	5	6000	4800	3/8	1/2	0.130	680	800	930	0.031
0.034	3/8	3/16	750	6	7000	5500	7/16	9/16	0.150	800	920	1100	0.034
0.040	3/8	3/16	900	6	7800	6300	7/16	5/8	0.160	1000	1270	1400	0.040
0.044	3/8	3/16	1000	8	8700	7000	7/16	11/16	0.180	1200	1450	1700	0.044
0.050	1/2	1/4	1200	8	9500	7500	1/2	3/4	0.190	1450	1700	2000	0.050
0.056	1/2	1/4	1350	10	10300	8300	9/16	7/8	0.210	1700	2000	2450	0.056
0.062	1/2	1/4	1500	10	11000	9000	5/8	1	0.220	1950	2400	2900	0.062
0.070	5/8	1/4	1700	12	12300	10000	5/8	1 1/8	0.250	2400	2800	3550	0.070
0.078	5/8	5/16	1900	14	14000	11000	11/16	1 1/4	0.275	2700	3400	4000	0.078
0.094	5/8	5/16	2400	16	15700	12700	3/4	1 3/8	0.285	3550	4200	5300	0.094
0.109	3/4	3/8	2800	18	17700	14000	13/16	1 1/2	0.290	4200	5000	6400	0.109
0.125	3/4	3/8	3300	20	18000	15500	7/8	2	0.300	5000	6000	7600	0.125

NOTES:

1. TYPES OF STEEL—301, 302, 303, 304, 308, 309, 310, 316, 317, 321, 347 AND 349
2. MATERIAL SHOULD BE FREE FROM SCALE OXIDES, PAINT, GREASE AND OIL
3. WELDING CONDITIONS DETERMINED BY THICKNESS OF THINNEST OUTSIDE PIECE "T"
4. DATA FOR TOTAL THICKNESS OF PILE-UP NOT EXCEEDING 4 "T". MAXIMUM RATIO BETWEEN TWO THICKNESSES 3 TO 1
5. ELECTRODE MATERIAL, CLASS 2, CLASS 3 OR CLASS 11

	CLASS 2	CLASS 3	CLASS 11
MINIMUM CONDUCTIVITY =	75%	45%	30% OF COPPER
MINIMUM HARDNESS =	75	95	98 ROCKWELL "B"

6. MINIMUM WELD SPACING IS THAT SPACING FOR TWO PIECES FOR WHICH NO SPECIAL PRECAUTIONS NEED BE TAKEN TO COMPENSATE FOR SHUNTED CURRENT EFFECT OF ADJACENT WELDS. FOR THREE PIECES INCREASE SPACING 30 PER CENT

the welding time is shorter than would be used for carbon steels because of the lower heat conductivity of stainless steel. Since the current is lower and the time is shorter, more accurate control of the current and time is required when welding stainless steel than carbon steel. The weld time should be accurate to within one cycle.

Squeeze time can be very short. All that is necessary is to be sure that there is enough time for the welding pressure to be fully applied. Squeeze time of 30 cycles is recommended. Hold time should be 30 cycles for thin stainless steel. This will allow the weld to cool enough so that there will be no loss of corrosion resistance. As the material being welded becomes thicker, the hold time should be lengthened. For stainless steel 1/8 inch thick, the hold time should be increased to 60 cycles.

Stainless steel retains its strength at much higher temperatures than does carbon steel. For this reason, higher welding pressures are required for spot welding stainless steel.

When welding the ferritic chromium stainless steels, the current should be increased slightly because these steels have a lower electrical resistance than the chromium-nickel stainless steels. Spot welding of hardenable chromium types requires a second pulse of current to temper the weld. Specific recommended practices for spot welding the hardenable types have not been compiled. However, the practices used for spot welding hardenable low-alloy steels can be used as a first approximation.

Applications. The Centaur missile is fabricated from thin sheets of cold-rolled Type 301 austenitic stainless steel joined by resistance spot welding. The use of liquid hydrogen fuel in this missile dictates the need for good spot-weld strength at a temperature of -423 F. General Dynamics-Convair found that the cross-tension strengths of spot welds in Type 301 stainless steel dropped off about 80 percent at -423 F as a result of carbide precipitation in the weld (Ref. 54,55). The welding procedures were modified to include a piece of nickel foil between the two pieces of stainless steel being welded. The welds made through this "sandwich" had increased nickel content and were not subject to carbide precipitation. The optimum thickness of nickel foil was 0.003 inch. Resistance spot welds in 0.011 and 0.016-inch-thick Type 301 stainless steel showed an increase in cross-tension strength of about 100 percent and in shear strength of 60 to 70 percent at -423 F when the nickel foil was used. Strength values for these welds are listed in Table **XXII.** The use of nickel foil also improved the tensile strength of resistance seam welds. Increase in strength at -423 F was 50 to 70 percent.

This technique was applied to the fabrication of simulated missile tankage weld joints. These simulated joints had the same design as actual joints in the Atlas and Centauer missiles. The two sheets of cold-rolled stainless steel were butt welded together by GTA welding and then roll-planished to cold work the weld metal to the same hardness and strength level as the base metal. The joint was then reinforced with a 4-inch-wide doubler of stainless steel of the same thicknes as the base metal. The doubler was attached to the base metal with four staggered rows of resistance spot welds. The spot welds were made both with and without the inclusion of 0.003-inch-thick nickel foil. The simulated joints were tested both in static and fatigue tension. Joints made with the nickel foil withstood up to 4000 cycles of 0 to 140,000 psi tensile stress without developing cracks. Without the nickel foil, cracks developed between 200 and 300 cycles. The static tensile strength of a joint that had undergone 2300 fatigue cycles was about 300,000 psi.

Figure 30 illustrates the equipment used in resistance-spot welding doublers and attachments to the stainless steel skin of Atlas and Centaur missiles.

As mentioned previously, the hardenable stainless steels require special welding techniques. The expanded use of Type 422 stainless steel in aircraft applications prompted a detailed study of the resistance spot welding characteristics of this alloy (Ref. 56). Welds were made in sheet 0.007-, 0.015-, and 0.022-inch thick. The recommended welding conditions resulting from this study are

TABLE XXII. STRENGTHS OF RESISTANCE SPOT WELDS IN TYPE 301 STAINLESS STEEL MADE WITH AND WITHOUT NICKEL FOIL (REF. 55)

Base Metal Thickness, inch	Nickel Foil Thickness, inch	Test Temperature, F	Shear Strength,[a] lb	Cross-tension Strength,[a] lb
0.011	None	75	390	213
	0.003	75	371	209
	0.005	75	361	212
	None	-423	379	65
	0.003	-423	615	131
	0.005	-423	580	134
0.016	None	75	652	354
	0.003	75	547	361
	0.005	75	545	356
	None	-423	487	78
	0.003	-423	865	149
	0.005	-423	846	168

(a) Average of ten tests.

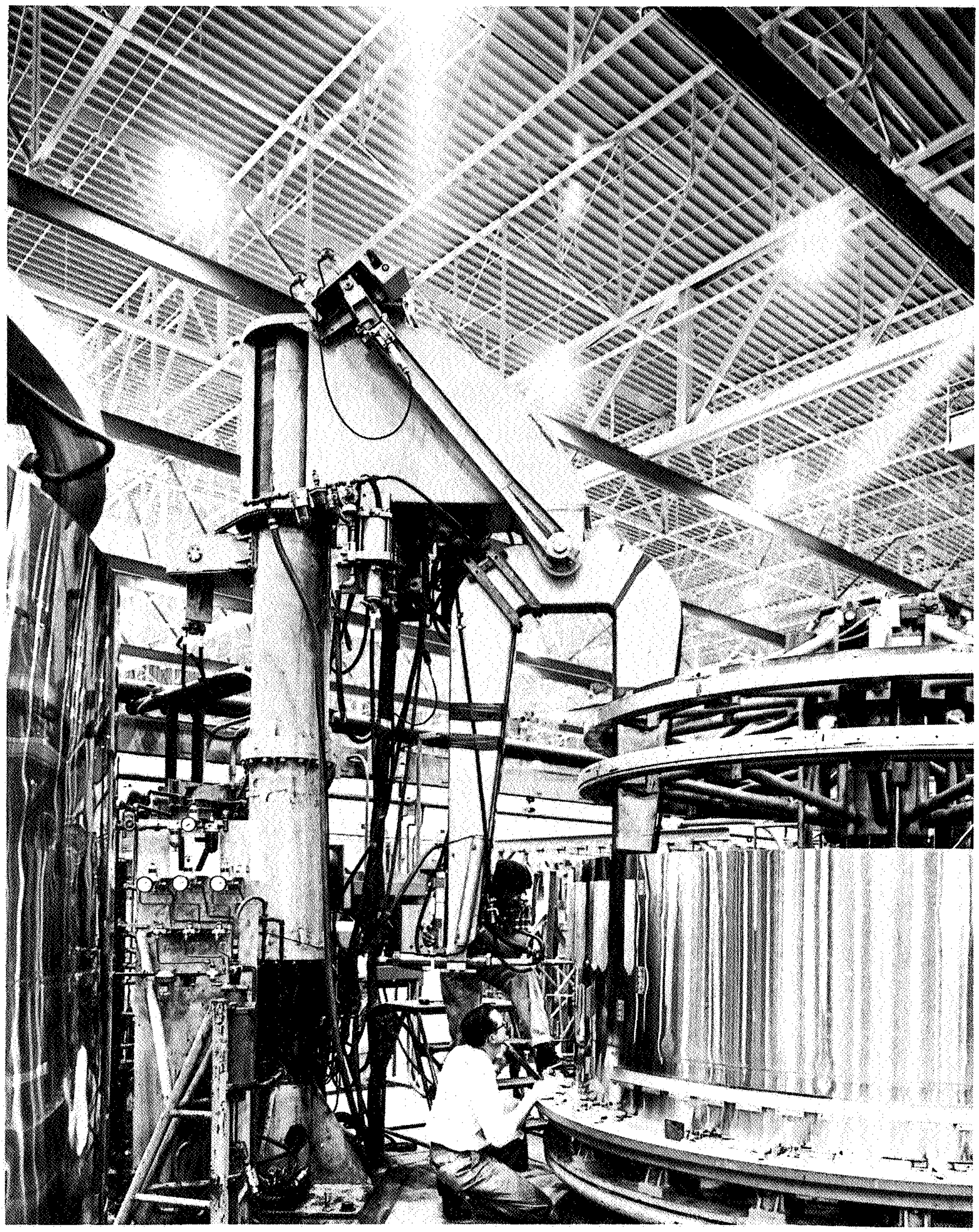


FIGURE 30. RESISTANCE-SPOT WELDING ATTACHMENTS TO STAINLESS STEEL MISSILE SKIN

(Courtesy Convair Division, General Dynamics Corporation)

given in Table XXIII. Strength properties of the welds are listed in Table XXIV. Several precautions should be observed in welding Type 422 stainless steel. These are: (1) close control of welding conditions is required so that the optimum heat cycle of the weld joint is obtained, (2) material should receive a uniform surface treatment so surface resistance and surface heat loss is uniform for all welds, (3) welding should be done only on machines designed to operate at the established optimum conditions. Either furnace or machine tempering produces satisfactory strength properties. However, in machine tempering, close control of the tempering current is required. Welds in Type 422 stainless steel should meet the following criteria:

(1) No fusion zone porosity or cracking

(2) Fusion zone penetration should be 30-80 percent of total sheet thickness

(3) Less than 5 percent sheet indentation or 10 percent sheet separation.

Projection Welding. Projection welding is a modification of resistance-spot welding. In spot welding, the point of current flow is determined by the size and shape of the contacting electrode. In projection welding, the point of current flow is controlled by projections or embossments on one or both of the parts being welded. The size of the electrode has no effect on the location of current and heat concentration.

Projection welding is used mainly for welding stamped or punched parts. The projections on such parts can be formed during the punching or stamping operation. It is also used for attaching machined parts such as screws or studs to sheet. The projections are machined on these fittings.

Recommended conditions for projection welding of stainless steel are given in Table XXV. The welding current is a little lower than would be used for making

TABLE XXIII. RECOMMENDED CONDITIONS FOR RESISTANCE-SPOT WELDING TYPE 422 STAINLESS STEEL (REF. 56)

Sheet Thickness, inch	Electrode Size, inch[(a)] Flat Face Diameter	Dome Radius	Weld Time, cycles	Weld Force, lb	Weld Current, amp	Chill Time,[(b)] Cycles	Temper Time, cycles	Temper Current, percent of Weld Current
0.022	1/4	6	8	600	4000 (3700-4500)	30	8	70 (55-75)
0.015	3/16	6	5	500	3700 (3400-4000)	30	5	80 (71-86)
0.007	5/32	6	4	400	3000 (2800-3300)	30	6	80 (75-84.5)

(a) RWMA Class III electrodes

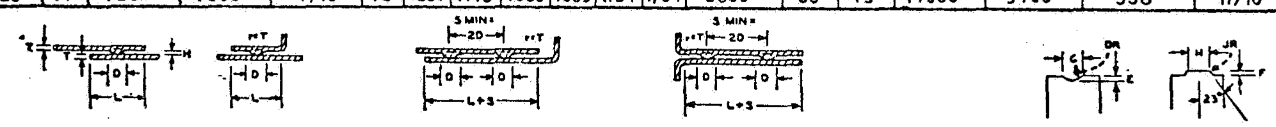
(b) Chill time is not necessarily optimum value but insures that weld zone is at room temperature before tempering.

TABLE XXIV. STRENGTH PROPERTIES OF RESISTANCE-SPOT WELDS IN TYPE 422 STAINLESS STEEL (REF. 56)

Sheet Thickness, inch	Condition	Tension-Shear Strength, lb	Cross-Tension Strength, lb	Ductility Ratio, percent	Weld Diameter, inch	Penetration percent
0.022	Furnace tempered	1240 (1140-1370)	290 (250-320)	23.4	0.130	60
	Machine tempered	1250 (1080-1340)	300 (240-350)	24.0	0.130	60
0.015	Furnace tempered	790 (730-800)	175 (166-175)	22.1	0.090	65
	Machine tempered	840 (706-872)	200 (126-326)	23.8	0.090	65
0.007	Furnace tempered	295 (275-325)	50 (35-65)	17.0	0.060	55
	Machine tempered	305 (285-330)	70 (57-70)	22.9	0.060	55

TABLE XXV. RECOMMENDED CONDITIONS FOR PROJECTION WELDING STAINLESS STEEL (REF. 53)

NOTES 1, 2, 3, 4		NOTES 5	NOTE 6	NOTE 7	SEE "PUNCH AND DIE DESIGN"								NOTE 8			NOTE 9		NOTE 10
THICKNESS OF EACH PIECE "T"	U.S.S. GAGE	DIA. OF PROJECTION "D" MIN. IN.	HEIGHT OF PROJECTION "H" IN.	ELECTRODE FACE DIA. d = 2xD (MIN.) IN.	PT. NO.	±.002 C IN.	Dr IN.	±.001 E IN.	±.001 F IN.	±.001 H IN.	Jr IN.	ELECTRODE FORCE LBS.	WELD TIME CYC.	HOLD TIME CYC.	WELDING CURRENT APPROX. AMPERES	MINIMUM SHEAR STRENGTH (UP TO 150,000 PSI. LB.)	DIAMETER OF WELD NUGGET AT INTERFACE IN.	MINIMUM CONTACTING OVERLAP "L" IN.
.014	29	.055	.015	1/8	1	.055	.033	.015	.015	.035	.005	300	7	15	4500	280	.112	1/8
.021	25	.067	.017	5/32	2	.067	.042	.017	.020	.039	.005	500	10	15	4750	440	.140	5/32
.025	24	.081	.020	5/32	3	.081	.050	.020	.025	.044	.005	600	12	15	5200	600	.140	3/16
.031	22	.094	.022	3/16	4	.094	.062	.022	.030	.050	.005	700	15	15	5750	850	.169	7/32
.034	21	.094	.022	3/16	5	.094	.062	.022	.030	.050	.005	700	17	15	5900	1000	.169	7/32
.044	19	.119	.028	1/4	6	.119	.078	.028	.035	.062	.005	700	20	15	6000	1300	.169	9/32
.050	18	.119	.028	1/4	7	.119	.078	.028	.035	.062	.005	1000	22	15	6500	1700	.225	9/32
.062	16	.156	.035	5/16	8	.156	.105	.035	.043	.081	.005	1200	25	15	7500	2250	.225	3/8
.070	15	.156	.035	5/16	9	.156	.105	.035	.043	.081	.005	1600	27	30	8800	2800	.281	3/8
.078	14	.187	.041	3/8	10	.187	.128	.041	.055	.104	.010	1900	30	30	10000	3200	.281	7/16
.094	13	.218	.048	7/16	11	.218	.148	.048	.065	.115	.010	1900	30	30	10000	4000	.281	1/2
.109	12	.250	.054	1/2	12	.250	.172	.054	.075	.137	1/64	2800	30	45	13000	5000	.338	5/8
.125	11	.281	.060	9/16	13	.281	.193	.060	.085	.154	1/64	2800	30	45	14000	5700	338	11/16



NOTES:

1. Types of Steel—309, 310, 316, 317, 321, 347, and 349. Nan-hardenable: maximum carbon content 0.15%.
2. Material should be free from scale, paint, grease, oil.
3. Size of projection usually determined by thickness of the thinner piece. Projection should be on thicker piece whenever practical.
4. Data applies to two thicknesses only where ratio of thicknesses is 3 to 1 or less.
5. Tolerance of diameter D is ± 0.003 in. up to 0.050 in. thickness and ± 0.007 in. up to 0.125 in., inclusive.
6. Tolerance of height H is ± 0.002 in. in material up to and including 0.050 in. and ± 0.005 in. up to and including 0.125 in.
7. Electrode material is Mallory 100 or Elkonite 10W3.
8. Weld time based on 60 cycles per second frequency.
9. Load of one projection weld only is based on tensile-shear specimens made from two coupons in which the overlap is equal to Ihe width of coupon.

Thickness Range	Width of Coupon	Length of Coupon
0.006–0.029"	¾"	3'
0.030-0.058"	1"	4"
0.059–0.115'	1½"	5"
0.116–0.190"	2'	6"

10. Weld should be located in center of overlap.

spot welds. Several projection welds can be made simultaneously. If these projections are relatively far apart, the current in the table should be multiplied by the number of projections. This current adjustment can be done best by trial and error. As a general rule, the welding current that does not cause excessive spitting is the best.

The weld time should be just long enough to include projection collapse. Once the projection has collapsed, large areas of the parts are in contact. With the current spread over this larger area, not enough heat is produced to keep the weld nugget molten. No useful purpose is served by continuing the welding current after projection collapse.

Proper welding pressure is very important. If it is too high, the projection will collapse before correct heating is achieved. If the force is too low, the projection may melt and blow out before the parts can be pushed together. Since the force is so critical, this is the first welding condition that should be set into the welding machine.

Round projections are the best shape to use. However, projections can also be square, oblong, or oval. With machined parts, as a stud or bolt, a ring shaped projection may be used as it is easy to machine. Suggested dimensions for projections in stainless steel parts are given in the table of welding conditions.

Resistance Seam Welding. Seam welding is nothing more than a series of overlapping spot welds. The chief difference between making seam welds and spot welds is the use of circular or wheel electrodes for seam welding. The principal advantage of seam welding over spot welding is that the joints are leaktight. However, there is more distortion in seam welding than in spot welding.

During welding, the electrodes rotate. Individual overlapping spot welds are created by coordinating the welding current time and wheel rotation. Wheel rotation can be either continuous or intermittent. Continuous rotation imposes additional limitations on the weld-cycle variations that can be used. For example, a forge-pressure cycle is not possible during continuous rotation. Forging pressure can be used with intermittent rotation as rotation takes place only after a weld is complete and before the next welding cycle starts.

The contour of the seam welding electrodes may be either flat with a beveled edge or a radius shape. The radius shape will give the best appearing seam welds. Recommended electrode width and surface radius for welding various thicknesses of stainless steel are given in the table of welding conditions, Table XXVI. As with spot welding, these conditions are only approximations. Exact conditions can be determined only by making test welds.

Distortion is a big problem in the seam welding of stainless steel. Staggering the welds on opposite sides of the assembly sometimes will help. If long seams are to be welded, skip welding will help to reduce distortion. The best method of minimizing distortion is to cool the weld with streams of water. A stream of water should be directed both in front and behind the point of contact of the wheel and part on both the top and bottom surfaces. Cooling water provides an added advantage in that by cooling the weld area rapidly, good corrosion resistance is maintained in the stainless steel.

Flash Welding. Flash welding is used extensively for joining stainless steel bars, tubes, wires, and thick strip and sheet end to end. Flash welding has advantages for welding stainless steels. All molten metal is squeezed out of the joint so there is no slow-cooled cast structure that might be subject to corrosion. The hot metal is upset during welding and this upsetting operation may improve the ductility of the heat-affected zones of the hardenable stainless steels.

Equipment. Equipment for flash welding is considerably different from equipment used for spot or seam welding. For welding, the parts are held firmly in

TABLE XXVI. RECOMMENDED CONDITIONS FOR RESISTANCE-SEAM WELDING STAINLESS STEELS (REF. 53)

THICKNESS "T" OF THINNEST OUTSIDE PIECE (SEE PAR 101 AND NOTES 1, 2,3 AND 4 BELOW)	ELECTRODE WIDTH AND SHAPE (SEE PAR. 102 AND NOTE 5 BELOW)	NET ELECTRODE FORCE (SEE PAR. 103)	ON TIME (SEE PAR. 104) CYCLES	OFF TIME FOR MAXIMUM SPEED (PRESSURE-TIGHT) (SEE PAR. 104) CYCLES		MAXIMUM WELD SPEED (SEE PAR. 104) IN. PER MINUTE		WELDS PER INCH (SEE PAR 104)		WELDING CURRENT (APPROX.) (SEE PAR 105)	MINIMUM CONTACTING OVERLAP (SEE PAR. 106 AND NOTE 6 BELOW)	THICKNESS "T" OF THINNEST OUTSIDE PIECE (SEE PAR. 101 AND NOTES 1, 2,3 AND 4 BELOW)
INCHES	W, IN., MIN.	LB	(60 PER SEC.)	2"T"	4"T"	2"T"	4"T"	2"T"	4"T"	AMPS.	IN.	INCHES
0.006	3/16	300	2	1	1	60	67	20	18	4000	1/4	0.006
0.008	3/16	350	2	1	2	67	56	18	16	4600	1/4	0.008
0.010	3/16	400	3	2	2	45	51	16	14	5000	1/4	0.010
0.012	1/4	450	3	2	2	48	55	15	13	5600	5/16	0.012
0.014	1/4	500	3	2	3	51	46	14	13	6200	5/16	0.014
0.016	1/4	600	3	2	3	51	50	14	12	6700	5/16	0.016
0.018	1/4	650	3	2	3	55	50	13	12	7300	5/16	0.018
0.021	1/4	700	3	2	3	55	55	13	11	7900	3/8	0.021
0.025	3/8	850	3	3	4	50	47	12	11	9200	7/16	0.025
0.031	3/8	1000	3	3	4	50	47	12	11	10600	7/16	0.031
0.040	3/8	1300	3	4	5	47	45	11	10	13000	1/2	0.040
0.050	1/2	1600	4	4	5	45	44	10	9	14200	5/8	0.050
0.062	1/2	1850	4	5	7	40	41	10	8	15100	5/8	0.062
0.070	5/8	2150	4	5	7	44	41	9	8	15900	11/16	0.070
0.078	5/8	2300	4	6	7	40	41	9	8	16500	11/16	0.078
0.094	5/8	2550	5	6	7	36	38	9	8	16600	3/4	0.094
0.109	3/4	2950	5	7	9	38	37	8	7	16800	13/16	0.109
0.125	3/4	3300	6	6	8	38	37	8	7	17000	7/8	0.125

NOTES:

1. TYPES OF STEEL– 301,302,303. 304, 308, 309, 310, 316, 317, 321,347 AND 349
2. MATERIAL SHOULD BE FREE FROM SCALE, OXIDES. PAINT. GREASE AND OIL
3. WELDING CONDITIONS DETERMINED BY THICKNESS OF THINNEST OUTSIDE PIECE "T"
4. DATA FOR TOTAL THICKNESS OF PILE-UP NOT EXCEEDING 4 "T". MAXIMUM RATIO BETWEEN THICKNESSES 3 TO 1
5. ELECTRODE MATERIAL, CLASS 3
   MINIMUM CONDUCTIVITY – 45% OF COPPER
   MINIMUM HARDNESS – 95 ROCKWELL "B"
6. FOR LARGE ASSEMBLIES MINIMUM CONTACTING OVERLAP INDICATED SHOULD BE INCREASED 30 PER CENT

two copper-alloy dies. One or both of these dies are movable. Current from a welding transformer passes through the dies and into the work. The parts initially may or may not be separated, but are advanced toward each other. At the first contact of the parts, the current causes melting of the metal and violent expulsion. This behavior continues until the base metal is heated to welding temperature. Then, the parts are forged together to complete the weld. Welding current usually is shut off at the time forging takes place.

The machine capacity required to weld stainless steels does not differ greatly from that required for steel. This is especially true for transformer capacity. The upset-pressure capacity for making flash welds in stainless steels is higher than that required for steel. Figures 31 and 32 show the transformer and upset capacity required for welding of different cross-sectional areas in stainless steels (Ref. 57). Also of importance is the fact that transformer-capacity requirements vary from one machine to another, depending upon the coupling between the parts and transformer.

Joint Design. Joint designs for flash welding stainless steels also are similar to those used for other metals. Flat, sheared, or saw-cut edges and pinch-cut rod or wire ends are satisfactory for welding. For thicker sections, the edges are sometimes beveled slightly. The overall shortening of the parts due to metal lost during welding should be taken into account so the finished parts will be of the desired length. Tables XXVII and XXVIII list the metal allowances used in making flash welds in stainless steel tubing, sheet, and solid bars.

Welding Procedures. The flash-welding conditions that are of greatest importance are flashing current, speed and time, and upset pressure and distance. With proper control of these variables, molten metal, which may be contamined, is not retained in the joint, and the metal at the joint interface is at the proper temperature for welding.

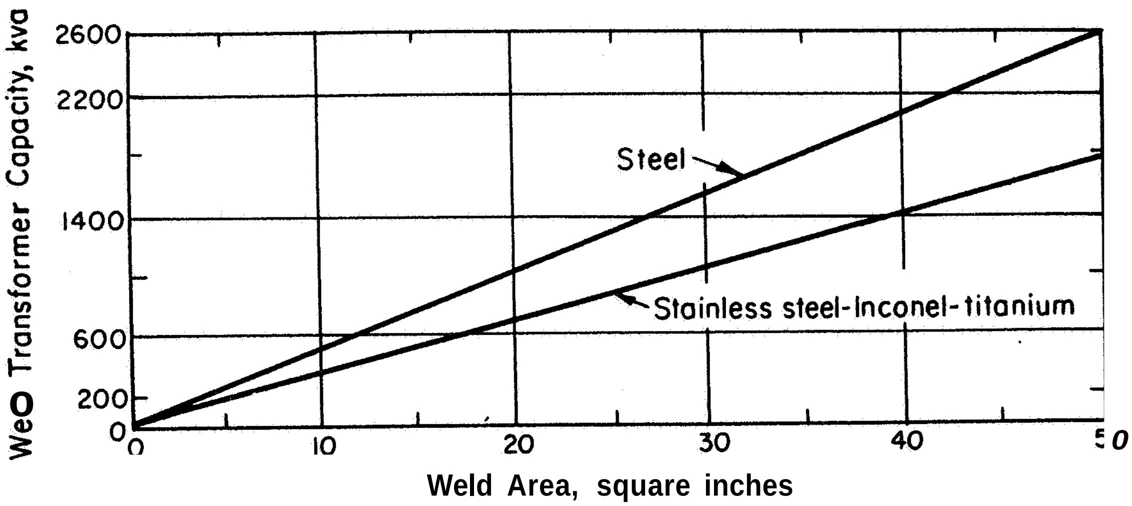


FIGURE 31. TRANSFORMER CAPACITY VERSUS WELD AREA
FOR FLASH WELDING (Ref. 57 as corrected)

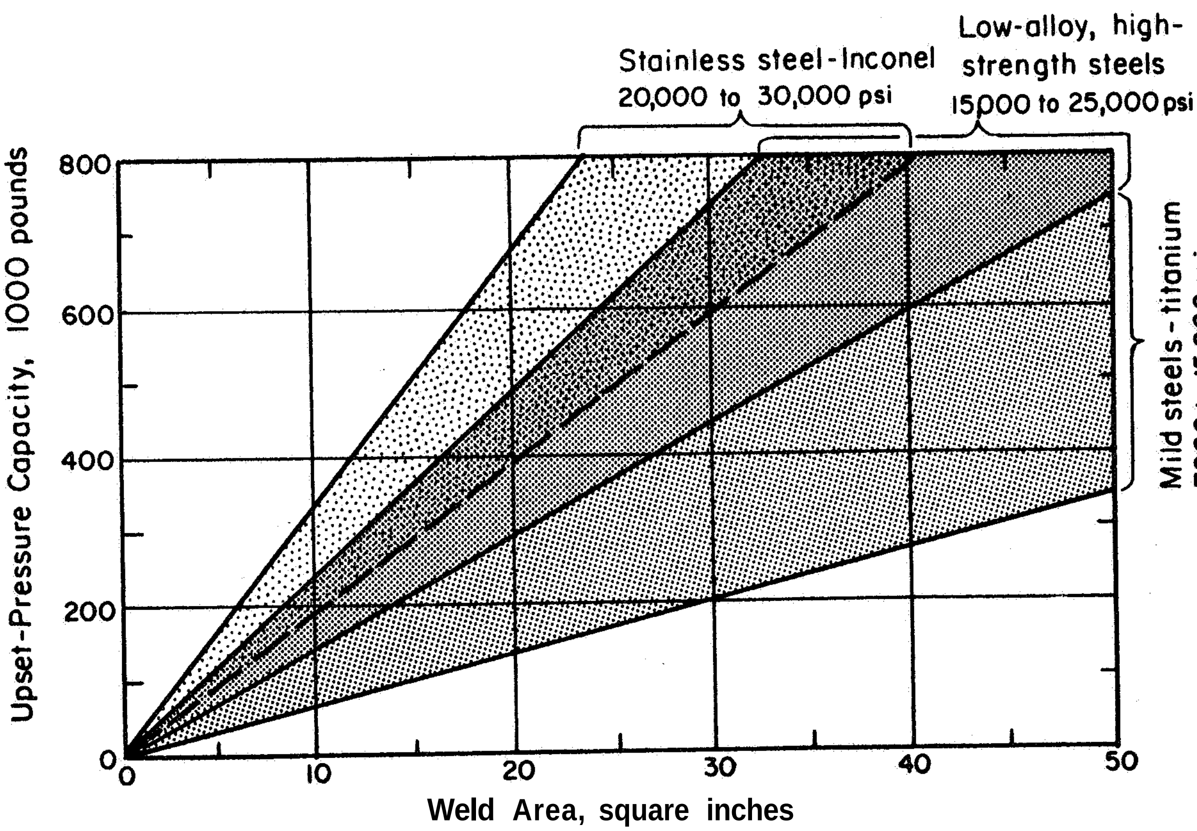
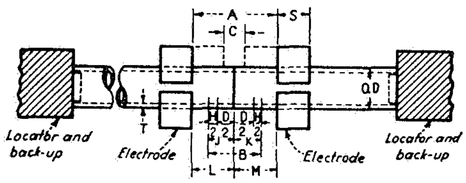


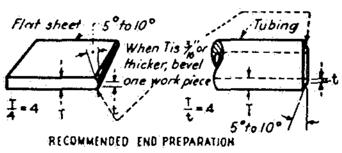
FIGURE 32. MAXIMUM MACHINE UPSET-PRESSURE REQUIREMENTS VERSUS
WELD AREA FOR FLASH WELDING (Ref. 57)

TABLE XXVII. DIMENSIONAL ALLOWANCES FOR FLASH WELDING STAINLESS STEEL TUBING AND SHEET (Ref. 53)

T in.	A in.	B in.	C in.	D in.	H in.	J = K in.	L = M in.	Flashing Time, Sec.	O D. in.	S with Locator	S without Locator
0010	0087	0057	0030	0.040	0017	0029	0.044	040	0250	0375	100
0.020	0156	0101	0055	0.070	0.031	0.051	0.078	0.65	0.312	0375	I 00
0.030	0.225	0145	0080	0.100	O M 5	0073	0113	0.85	0.375	0375	1.50
0.040	0287	0182	0105	0124	0.058	0.091	0.144	110	0.500	0.375	1.75
0050	0350	0220	0130	0153	OW7	0110	0175	135	0750	0.500	200
0.060	0.406	0261	0.145	0.180	0081	0131	0203	1.65	1.00C	0 7 M	250
0.080	0529	0344	0185	0236	0108	0172	0164	215	1.50	1.000	300
0.100	0637	0412	0225	0282	0130	0 2 W	0319	2.85	2.00	125	
0120	0748	0483	0265	0.330	0153	0242	0.374	3.30	2.50	175	
0140	0862	0.552	0310	0382	0170	0276	0431	3.85	3.00	2.00	
0 160	0958	0608	0350	0420	0 188	0.304	0479	4 50	3 50	2 25	
0180	1.053	0663	0390	0457	0.206	0.332	0527	525	4.00	250	
0.200	1141	0711	0430	0487	0224	0356	0570	6.00	4 5 0	275	
0250	1298	0798	0.500	0548	0.250	0.399	0649	8.00	5.00	175	
0300	1437	0877	0560	0607	0270	0439	0718	10.5	5 5 0	3.00	
0.350	1587	0.957	0630	0.660	0297	0479	0794	13.5	6 0 0	325	
0.400	1702	1021	0680	0698	0324	0511	0851	165	6 5 0	350	
0460	1789	1069	0720	0727	0.342	0535	0894	19.0	7 0 0	375	
0.500	1.866	1116	0750	0765	0351	0558	0933	125	7 5 0	4.00	
0550	1950	1160	0790	0790	0370	0.580	0975	250	8.00	425	
0600	2012	1191	0820	0814	0378	0596	1006	28.0	8.00	450	

Note – These data rover standard types of stainless in the 300 and 400 series and are bared on welding without preheating, both pieces having the same welding characteristics





T = Tube wall or sheet thickness
A = Initial die opening
B = Material lost
C = Final die opening

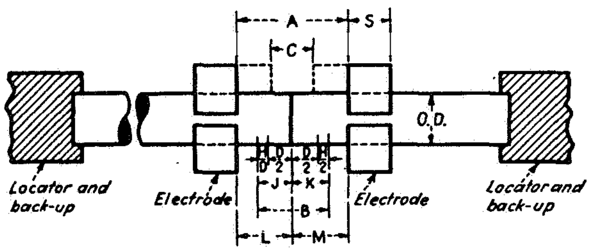
D = Total flash-off
H = Total upset
J = K = Material lost per piece

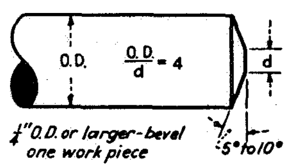
L = M = Initial extension per piece
OD = Outride dia of tubing
5 = Minimum length of electrode contact

TABLE XXVIII. DIMENSIONAL ALLOWANCES **FOR** FLASH WELDING STAINLESS STEEL **BARS (Ref.** 53)

O O	A n	B in.	C in.	D	H in	J = K n	L = M in.	Flashing Time. sec.	O O	S with locator	S without locator
0 050	0100	0050	0050	0 040	0010	0025	0 050	0 40	0 250	0375	1.00
0100	0182	0.082	0.100	0.062	0 020	0.041	0.091	0 75	0.312	0375	1.00
0 150	0 270	0.120	0.150	0.090	0 030	0060	0135	115	0 375	0375	150
0200	0 350	0.150	0.200	0110	0 040	0075	0 175	150	0 500	0.375	175
0250	0430	0180	0250	0130	0 050	0 090	0215	1.90	0 750	o m	2.00
0 300	0510	0.210	0.300	0 150	0 060	0 105	0 255	2.25	1.000	0.750	2.50
0350	0.600	0250	0350	0.180	0 070	0125	0 300	2 75	1.50	1.000	3.00
0400	0 685	0285	0.400	0.205	0 080	0 143	0 343	3 25	2 00	1.25	
0 450	0 770	0320	0450	0 230	0 090	0 160	0 385	3 75	2 50	175	
0500	0 850	0350	0.500	0 250	0100	0 175	0 425	4 25	3.00	2.00	
0550	0940	0.390	0550	0 280	0110	0195	0470	5.00	3 50	2 25	
0.600	1.025	0 425	0.600	0 305	0 120	0213	0 513	5 50	400	2.50	Do not recommend without use of backups
0 650	1.100	0.450	0.650	0 325	0125	0225	0 550	6 75	4 50	2.75	
0700	1 180	0.480	0 700	0 350	0 130	0 240	0 590	7 50	5.00	2.75	
0750	1 260	0510	0.750	0 375	0 135	0 255	0 630	8 25	5 50	3.00	
0 800	1340	0540	0.800	0 400	0 140	0 270	0670	9 0 0	6 00	3.25	
0 850	1420	0.570	0.850	0425	0 145	0 285	0710	9 75	6 50	3.50	
0900	1.500	0 600	0.900	0450	0150	0.300	0750	10 50	7.00	3.75	
0950	1580	0.630	0.950	0.475	0155	0.315	0790	11 75	7 50	4.00	
1.000	1.660	0.660	1.000	0500	0160	0330	0830	13.00	8.00	4.25	
1050	1740	0.690	1 050	0.525	0 165	0345	0870	14 75	8.00	4.10	
1.100	1.820	0.720	1.100	0 550	0.170	0 360	0910	16 50	9 0 0	4.75	
1.150	1.900	0.750	1.150	0.575	0 175	0 375	0 950	18 25	9 50	5.00	
1.200	1980	0.780	1.200	0.600	0 180	0 390	0.990	20 00	10.00		
1.250	2.060	0.010	1.250	0.625	0 185	0 405	1030	22 50			
1.300	2.140	0.140	1.300	0.650	0 190	0 420	1 070	25 00			
1400	2 300	0.900	1.400	0.700	0 200	0450	1150	3000			
1.500	2 460	0.960	1.500	0.750	0 210	0480	1.230	30 00			
1.600	2 620	1.020	1.600	0.800	0 220	0510	1.310	45 00			
1700	2 780	1.080	1.700	0.050	0 230	0540	1390	54 00			
1800	2 940	1.140	1.800	0.900	0 240	0 570	1.470	63 00			
1.900	3 100	1.200	1.900	0.950	0 250	0.600	1 550	75 00			
2.000	3 260	1.260	2.000	1.000	0 260	0630	1630	90.00			

Note—These data cover standard types of stainless in the 300 and 400 series and are based on welding without preheating, both pieces having the same welding characteristics. The values apply only when ratio of maximum to minimum cross-sectional dimensions is less than 1 to 1.5





RECOMMENDED END PREPARATION

O 0. = Diameter of rounds or minimum dimension of other sections
A = Initial die opening
B = Material lost
C = Final die opening
D = Total flash-off
H = Total upset
J = K = Material lost per piece
L = M = Initial extension per piece
S = Minimum necessary length of electrode contact

Generally, high flashing speeds and short flashing times are used when it is desirable to minimize weld contamination. Also, the use of a parabolic flashing curve is more desirable than the use of a linear flashing curve because maximum joint efficiency can be obtained with a minimum of metal loss.

Flash welding variables vary from machine to machine and application to application. Welding current and arc voltage depend on the transformer tap that is used.

When welding the hardenable chromium stainless steels, it may be advantageous to shut off the current gradually so that thwweld area cools slowly to prevent brittle welds. For welds of the highest quality in any of the stainless steels, a protective atmosphere of argon or helium may be used around the weld area.

SOLID-STATE WELDING

. In solid-state welding, two or more solid phases are metallurgically joined without the creation of any liquid. Welding occurs by the action of atomic forces and is not the result of only mechanical interlocking. For engineering purposes, solid-state welding is conveniently divided into two categories, diffusion welding and deformation welding. In diffusion welding, deformation is restricted to that amount necessary to bring the surfaces to be joined into intimate contact and diffusion is the primary mechanism of weld formation. In deformation welding, diffusion plays a less important role and deformation is the primary factor in creation of the weld. Both deformation and diffusion occur in these two solid-state welding processes.

These processes are described in more detail below and experience in the application of these methods to precipitation-hardening stainless steels is presented. The fundamentals of solid-state welding have been extensively discussed in a previous report of the Redstone Scientific Information Center (Ref. 58).

Diffusion Welding. Solid-state diffusion welding is a joining method in which metals are joined with the application of pressure and heat. Pressure is limited to the amount that will bring the surfaces to be joined into intimate contact. Very little deformation of the parts takes place. Solid-state diffusion welding does not permit melting of the surfaces to be joined. Once the surfaces are in intimate contact, the joint is formed by diffusion by atomic species across the original interfaces.

Some of the merits of the process that make it attractive as a method of manufacturing are as follows:

(1) Multiple welds can be made simultaneously.

(2) Welds can be made that have essentially the same mechanical, physical, and chemical properties as the base metal.

(3) Welding can be done below the recrystallization temperature of most materials.

(4) The formation of brittle compounds can be avoided provided that proper materials and welding conditions are selected.

(5) For each material combination, there are several combinations of parameters that will produce welds.

(6) Segregation and dilution of alloy or strengthening elements is eliminated.

Diffusion welding is primarily a time and temperature-controlled process. The time required for welding can be shortened considerably by using a high welding pressure or temperature because diffusion is much more rapid at high temperatures than at low temperatures. Both the welding time and temperature often can be reduced by using an intermediate material of different composition than the base metal to promote diffusion. This procedure reflects the increase in diffusion rate that is obtained by the introduction of a dissimilar metal.

The steps involved in diffusion welding are as follows:

(1) Preparation of the surfaces to be welded by cleaning or other special treatments,

(2) Assembly of the components to be welded.

(3) Application of the required welding pressure and temperature in the selected welding environment.

(4) Retention of the welding pressure and temperature for the desired welding time.

(5) Removal of the welded parts from the welding equipment for inspection, testing, or placement in service.

Cleaning stainless steel prior to diffusion welding can be accomplished using the following procedure:

(1) Degrease.

(2) Pickle in 15 weight percent HNO_3-1.5 weight percent HF-83.5 weight percent H_2O.

(3) Rinse in deionized water.

(4) Dry.

A more complex procedure that has been successfully used prior to gas pressure bonding of 347 stainless steel consisted of mechanically preparing the pieces, degreasing in alcohol, pickling in 10 volume percent HNO_3-2 volume percent HG aqueous solution for 2 minutes at 120 to 140 F, and rinsing in cold running water. Following these steps, a washing and cleaning cycle was conducted as follows:

(1) Placed in trichlorethylene vapor bath (5 minutes).

(2) Scrubbed in methyl ethyl ketone.

(3) Scrubbed in 200-proof alcohol.

(4) Placed in 200-proof ultrasonic bath (5 minutes).

(5) Scrubbed in a hot Alcanox solution (180 F).

(6) Rinsed in cold running water.

(7) Placed in 200-proof ultrasonic bath (5 minutes).

(8) Rinsed in cold running water.

(9) Rinsed in hot water (180 F).

(10) Blown dry with filtered air.

Selection of a degreasing chemical depends on the condition of the surfaces. Common degreasing agents include acetone, alcohol, methyl ethyl ketone, trichloroethylene liquid or vapor, and perchloroethylene liquid or vapor, Any of these should be suitable.

Final drying of metal parts can be accomplished in a number of ways. These include:

(1) Blasting with a clean, dry gas (e.g., filtered air or nitrogen).

(2) Swabbing with a volatile solvent such as alcohol.

(3) Immersing in a hot vapor such as trichloroethylene or perchloroethylene and subsequently allowing the pieces to dry in air.

(4) Placing in a heated oven.

If the welding is to be conducted in a vacuum, drying can be readily accomplished immediately prior to bringing the faying surfaces into contact. Volatile surface impurities will be desorbed in vacuum at an elevated temperature.

Tables XXIX, XXX, and XXXI summarize the conditions used in diffusion welding stainless steel to itself and to aluminum and beryllium.

Deformation Welding. Deformation welding differs from diffusion welding primarily because a large amount of deformation takes place in the parts being joined. The deformation makes it possible to produce a weld in such shorter times and frequently at lower temperatures than are possible with diffusion welding. When joining assemblies at elevated temperatures, bonding pressures and atmospheres often differ considerably from room-temperature values because of such factors as outgassing and softening of the materials. Arrangements must be made to control these factors under actual bonding conditions. Welding deformations as great as 95 percent may be used, The steps involved in deformation welding are very similar to those used in diffusion welding.

Roll Welding. Roll welding is a solid-state-deformation-welding process that has been used for the fabrication of structural shapes and sandwich panels (Refs. 59, 60, 61). A variety of materials including the 300

TABLE XXIX. SUMMARY OF DIFFUSION WELDING DATA FOR JOINING STAINLESS STEEL TO STAINLESS STEEL

Alloy and Condition	Specimen Geometry	Surface Preparation	Intermediate	Welding Method*	Welding Temp, °F	Welding Pressure, psi	Welding Time, hr	Welding Atmosphere	Weld Strength, psi	Type of Failure	Reference	Comments
347 S.S.	B t d		Au-plated surfaces, Cu foil between 0.0005-in. Au plate and 0.008-in. Cu foil	Press, in tapered liner	50	30,000	1	Air	36,900 avg		62	Specimens were leaktight; no welds produced at 300 F
					700	25,000	0.25	Air	24,500 avg			
347 S.S.	--	--	None	GPB	1830	12,000	1/3	Evacuated container			63	Minimum welding conditions
					2190 2190	2,000 12,000	1/3 1/12				64	
S.S.	--	--	None	GPB or press	2100	10,000	1-3	--	--	-	65	General conditions for diffusion welding
321 S.S.	X o cycomb panel	--	--	--	200	6	1/20	--	--	-	66	
347 S.S. 304 S.S.		Mechanically clean, alcohol rinse, HNO_3-HF pickle, water rinse, wash	None	GPB	200	300-500 til 2100 F reached, then 10,000	2	Evacuated container			67,68	Slight grain growth and excellent welding when examined metallographically
304, 316, 347, 410 S.S., 304L		Pickled, as-rolled, belt abraded, or milled	None	GPB	2100 approx	10,000 (gas)	1 3	Ditto	100 percent efficiency		69,70	
347 S.S.	Single lap 1/16 x 3/8 x 2 in. Overlap = 1.5 t = 3/32 in.		Ni-3 wt % Be 0.0004-in. foil	Static weight	2110	Nil. 3/8 in. diam by 1/2-in. stainless steel weight	1 12	Vacuum 7×10^{-5} torr	39,600	Through weld in shear	71	
347 S.S.	Double lap 1/8 x 3/8 x 2 in. Overlap = 1.5 t = 3/16 in.		Ni-20 Cr.-0.3 Mn-3 Be (wt %) 0.004-in. thick foil	Ditto	[illegible] and 2100	Ditto	1/6	Ditto	17,500 avg at 1500 F	In parent metal	71	Weld strength was 20,000 psi at 2100 F welding temperature and 15,000 psi at 2080 F

* GPB - gas-pressure bonding

TABLE XXX. SUMMARY OF DIFFUSION WELDING DATA FOR JOINING STAINLESS STEEL TO BERYLLIUM

Alloy and Condition	Specimen Geometry	Surface Preparation	Intermediate	Welding Method*	Welding Temp, °F	Welding Pressure, psi	Welding Time, hr	Welding Atmosphere	Weld Strength, psi	Type of Failure	Reference	Comments
Be to 316 S.S.	Wafer laminate, metallographic specimen, 1/2-in. diam by 1/16 in.	Metallographic to 0.5-micron diamond abrasive and then Linde B alumina	None	Threaded plug, 60 ft-lb torque	1800	--	4	Vacuum 10^{-5} torr	-	--	72	Measurable intermetallic zone; multiple fractures appeared at interface that had high hardness
Be to 316 S.S.	Ditto	Ditto	0.002-in. Cu foil	Ditto	1500	--	4	Ditto	-	--	73	Welded; Cu failed to retard diffusion of Be into S. S.; failure occurred in the Be
Be to 316 S.S.	Stainless tube (0.5-in. OD by 0.049-in. wall) inside a Be tube (1-1/4-in. OD)	Stainless was Ag plated and was brushed. Be was etched, Ag plated and reamed	Approx 0.0005-in. Ag on stainless OD and Be ID	DTE	1450	--	2	Vacuum 7×10^{-5} torr	-	--	74	Fine partition line periodically observed at 300 magnifications

*DTE - differential thermal expansion

TABLE XXXI. SUMMARY OF DIFFUSION WELDING DATA FOR JOINING STAINLESS STEEL TO ALUMINUM

Alloy and Condition	Specimen Geometry	Surface Preparation*	Intermediate	Welding Method	Welding Temp, °F	Welding Pressure, psi	Welding Time, hr	Welding Atmosphere	Weld Strength, psi	Type of Failure	Reference	Comments
2219-T62 Al to 321 S.S.	Single lap	Wiped with MEK after plating, 5 min before bonding	0.00015-in. Ag plate on both specimens		500	26,000	3.5		12,800 and 12,900		74	Complete solid-state diffusion; these are best conditions found
	Ditto	Rubbed with 320 SiC paper followed with MEK	None		600	21,400	4.0		1,730 and 450		74	
	Ditto, 0.12-in.-thick lapped sheets	Ag plate not cleaned prior to bonding	0.0015-in. Ag plate on both specimens	20-ton press, heated platens	700	15,000 initially, raised at 700°F to deform Al	1/3		17,690 16,410 15,800		74	Deformation limited to 0.004 in.
	Double lap	Ditto	Ditto	Ditto	Ditto	Ditto	Ditto		14,500 15,880 14,280		74	Ditto
B18S Al to 303 S.S.	Butted rods 1-in. diam x 1 in.	Al: No. 50 grit belt grind 303: No. 240 grit + H_3PO_4 anodic etch	None	Press, sleeve dies, flame heated	750-850	10,000 at 850°F 18,000 at 750°F	1/12	Air	31,000-50,000		75	B18S: Al-4Cu-2Ni-0.7Si-1.5Mg
2024 Al to 1020 steel	Single lap 1/2-in. overlap by 1/2 in. wide by 1/4 in. thick	1020 rubbed with alcohol; 2024 cleaned with NaOH and with HNO_3	0.005-in.-thick BAg10 braze alloy	Press	800 optimum	2400 optimum	2 optimum	Air	4600 max		76	Less than 3 percent deformation

* MEK - methyl ethyl ketone

series of stainless steels has been investigated and found suitable for this method of fabrication. The process utilizes conventional techniques and equipment for preparation of packs in which the structures are encapsulated for roll welding. Welding is accomplished in a standard hot-rolling mill. An especially important attribute of roll welding is that neither new machines nor unusual techniques are required. Forming of the roll-welded structures is accomplished on hydropresses, brakes, and by other standard airframe manufacturing equipment.

Roll. welding of truss-core sandwich structures usually includes the following processing steps:

(1) Prepare the core, by corrugating or shaping to the desired configuration.

(2) Fill the spaces between corrugations or ribs, using filler bars of mild steel or other appropriate metal.

(3) Position the face sheets on the core-and-filler-bar section.

(4) Place the sandwich in an appropriate yoke.

(5) Weld covers to the yoke to form an airtight pack.

(6) Evacuate the pack, to protect against oxidation.

(7) Hot roll the pack, in the same manner as a single metal plate, to the desired reduction in thickness; welding is accomplished in the same operation.

(8) Contour the pack, if contouring is required, by appropriate hot or cold rolling or other forming process.

(9) Remove the covers, mechanically.

(10) Remove the filler bars chemically, leaching with dilute nitric or other appropriate acid.

Primary advantages of roll-welded sandwich structures include: (1) the fabrication of complex contoured surfaces are possible; (2) a reliable diffusion bond between core and faces, with the properties and strength of the base metal can be achieved; **(3)** low cost compared to conventional brazed sandwich structures. These advantages make it a suitable method for fabricating fuel tanks, solid propellant .engine cases, pressure vessels and space vehicle structures of many kinds.

BRAZING

Stainless steels can be readily brazed providing care is taken in the selection of the brazing filler metal and close control is exercised over the brazing operation. The stainless steel alloy being brazed and the intended service of the brazed joint dictate the brazing technique, materials, and equipment required.

The brazing cycle used for most of the chromium-nickel stainless steels should avoid prolonged exposure to temperatures in the range of 900 to 1300 F if the brazed joint will be exposed to a corrosive environment. This is because carbide precipitation will reduce the corrosion resistance of the stainless steel. Carbide precipitation can be avoided by:

(1) Choosing a brazing filler alloy with a melting temperature above 1300 F.

(2) Cooling the parts quickly after brazing to minimize the time in the critical temperature range.

(3) If the chosen filler metal flows in the critical temperature range, the brazing operation should be one that insures rapid heating and cooling. Induction or torch brazing could be used but not furnace brazing.

(4) Use a stabilized or low-carbon grade of stainless steel that is not subject to carbide precipitation.

(5) Heat treat the brazed part to dissolve the precipitated carbides. This step can be used only if a high-melting temperature brazing alloy is used.

If a corrosive environment is not anticipated, these precautions are not required, Chromium-nickel stainless steels should be in the annealed condition when brazed and the parts should not be stressed during the brazing operation. These steels are subject to stress corrosion by molten brazing alloys and cracking of the metal adjacent to the braze metal can occur if the metal is under stress while exposed to the molten brazing metal.

When the hardenable chromium stainless steels are brazed, the effect of the brazing heat on the strength of the steel may have to be taken in account. If the brazing temperature is below the hardening temperagure, some loss in strength can occur because of tempering. On the other hand, if the brazing temperature is above the hardening temperature, brazing and hardening can be carried out at the same time.

Brazed joints made in the chromium stainless steels with silver-base brazing alloys may be subject to corrosion along the stainless steel-brazing alloy interface (Ref. 77). This problem usually is solved by using a nickel-bearing silver-base brazing alloy. Although joints in Type 430 stainless steel may still exhibit this type of corrosion although to a lesser degree.

The service temperature is another factor that must be taken into account in selecting the brazing alloy. Stainless steels often are used for their strength and resistance to scaling at high temperatures. With few exceptions, the strength and oxidization resistance of copper-base and silver-base brazing alloys fall off rapidly above 500 F and 800 F, respectively. For service temperatures up to 1000 F, the copper-manganese-nickel brazing alloys are used. The nickel-base brazing alloys are used for service above 1000 F.

There are a large variety of brazing filler metals that can be used to braze stainless steels. Selection of the brazing alloy must be made with consideration for the factors discussed above. The list of brazing filler metals which can be used on the stainless steels is almostunlimited. Commercial filler metals are available which contain copper, gold, silver, palladium, nickel, manganese, iron, and many other elements either as the base or as additional elements. Some typical filler metal alloys for stainless steels are listed in Tables XXXII and XXXIII..

TABLE XXXII. COMMONLY USED NOBLE METAL BRAZING ALLOYS FOR STAINLESS STEELS

Composition, weight per cent								Flow Temperature, F	AMS Number
Ag	Au	Pd	Cu	Li	Zn	Cd	Other		
45	--	--	15	--	16	24	--	1145	4769
50	--	--	15.5	--	16.5	18	--	1175	4770B
56	--	--	22	--	17	--	5 Sn	1205	--
50	--	--	15.5	--	15.5	16	3 Ni	1270	--
35	--	--	26	--	21	18	--	1295	4768
61.5	--	--	24	--	--	--	14.5 In	1305	--
60	--	--	30	--	--	--	10 Sn	1325	--
45	--	--	30	--	25	--	--	1370	--
72	--	--	27.8	0.20	--	--	--	1400	--
50	--	--	34	--	16	--	--	1425	--
40	--	--	30	--	28	--	2 Ni	1435	--
72	--	--	28	--	--	--	--	1435	--
54	--	--	40	--	5	--	1 Ni	1575	4772A
92.5	--	--	7.3	0.20	--	--	--	1635	--
54	--	25	21	--	--	--	--	1742	--
63	--	--	27	--	--	--	10 In	1346	--
75	--	20	--	--	--	--	0.5 Mn	2050	--
--	37.5	--	62.5	--	--	--	--	1841	--
--	82	--	--	--	--	--	18 Ni	1742	--
--	80	--	20	--	--	--	--	1666	--
--	35	--	62	--	--	--	3 Ni	1877	--
--	50	25	--	--	--	--	25 Ni	2050	--
--	70	8	--	--	--	--	22 Ni	1899	--
--	35	--	62	--	--	--	3 Ni	1886	--
--	81.5	--	16.5	--	--	--	2 Ni	1697	--

TABLE XXXII. (CONTINUED)

Composition, weight per cent								Flow Temperature, F	AMS Number
Ag	Au	Pd	Cu	Li	Zn	Cd	Other		
5	75	--	20	--	--	--	--	1643	--
--	60	--	37	--	--	--	3 In	1652	--
--	--	60	--	--	--	--	40 Ni	2260	--
27.5	--	50	23.5	--	--	--	--	1515	--
54	--	25	21	--	--	--	--	1728	--

TABLE XXXIII. COMMONLY USED NICKEL-BASE BRAZING ALLOYS FOR STAINLESS STEELS

Composition, weight per cent						Brazing Temperature Range, F	AMS Number
Cr	Si	B	Fe	Ni	Other		
13.0-20.0	3.0-5.0	2.75-4.75	3.0-5.0	Balance	1.0Co max, 0.6 C max	1975-2200	4775
6.0-8.0	3.0-5.0	2.5 -3.5	2.0-4.0	Balance	1.0Co max, 0.5 C max	1850-2150	4777
--	3.0-5.0	1.8- 3.5	--	Balance	1.0Co max, 0.5 C max	1850-2150	4778
--	--	--	--	Balance	11 P, 0.1C	1700-1850	--
19	10	--	--	Balance	0.1 C	2100-2200	--
13	--	--	--	Balance	10 P, 0.1C	1700-1950	--
--	8	--	--	Balance	17Mn, 0.1C	1900-2100	--
--	3.5	1.8	--	Balance	0.06 C	1950-2150	4779
7	4.5	3.2	3.0	Balance	6W, 0.1C	1950-2150	--
4	--	0.9	--	Balance	45Mn, 0.1C	2000-2150	--
3.5	2.5	0.9	1.0	Balance	35Mn, 0.1C	1950-2050	--
--	4.5	3.3	--	Balance	20Co	1950	--
--	11.0	--	30.0	Balance	3.5 P, 5.4Mo	--	--
33	4	--	--	Balance	25 Pd	2150-2175	--

Stainless steel must be carefully cleaned before brazing to remove all foreign material (dirt, grease, markings, etc.) and as much of the oxide film as possible., This oxide film is very tenacious and difficult to remove by fluxes and reducing atmospheres alone. Precleaning eases the job of the flux or atmosphere. Precleaning consists of degreasing in a solvent or alkaline cleaner followed by pickling in an acid solution. Filing or stainless steel wire brushing also may be used for cleaning.

Most brazing methods such as torch, induction, or furnace can be used with stainless steels. Methods which do not protect the assembly during brazing require fluxes and pose subsequent flux removal problems. They may also produce weakened joints due to entrapment of flux residues. Consequently, most brazing operations on critical assemblies of stainless steel are carried out in a protective atmosphere. Dry, oxygen-free atmospheres that are used include inert gases, hydrogen, and vacuum. Atmospheres having dew points below -40 F are necessary to prevent oxidation of the base metal during heating. Carbonaceous material should not be permitted in the brazing atmosphere or in the furnace. Carbon in contact with the brazement and carbonaceous atmospheres will carbonize the stainless steel and reduce its corrosion resistance.

After brazing, all flux or stop-off residues should be carefully cleaned from the parts. These residues may cause corrosion or adversely affect the properties of the stainless steel in service.

Applications. One of the most important applications in the brazing of stainless steel is the joining of tubing for aircraft hydraulic or rocket propulsion fluid systems. The system components are joined by the use of commercially manufactured brazing fittings. These techniques were developed by North American Aviation for use in construction of the X-15 and XB-70.

North American Aviation also investigated the feasibility of using these brazing techniques and fittings for rocket propulsion fuel systems (Ref. 78). Standardized procedures, fittings, and equipment have now been developed and are available commercially for fabricating stainless steel fluid lines (Ref. 79). Two types of fittings are available and are shown in Figure 33. The brazing alloy is inserted in the grooves in the fittings. For brazing Type 321 stainless steel tubing, the brazing alloy used is 82 gold-18 nickel. After the ends of the tubes and the fitting are assembled, an induction brazing fixture is placed around the assembly (Figure 34). The interior of the fixture is purged with argon gas. The brazing alloy is melted by induction heating the fitting and ends of the tubes. Fittings for Type 321 stainless steel are available as T's, elbows, and unions for tubing ranging from 1/4 inch to 2-1/2 inch diameter.

The steps for induction brazing of tubing are as follows (Ref. 79):

(1) Prepare tube ends by removing all burrs.

(2) Check tube size. The outside diameter of the tubing should be 0.003 ± 0.0005 inch smaller than the inside diameter of the fitting. Sizing tools are used to correct over or under size of the tubing.

(3) Degrease tube ends. Remove surface oxide by glass-bead peening then degrease again and dry with a clean, lint-free cloth.

(4) Align tubes with a straightedge. Misalignment should not exceed 0.060 inch.

(5) Remove fitting from the plastic bag in which it is packed. The operator should wear clean, Lint-free cotton gloves.

(6) Place fitting and brazing alloy rings in place on ends of tubing.

(7) Place brazing tool around joint.

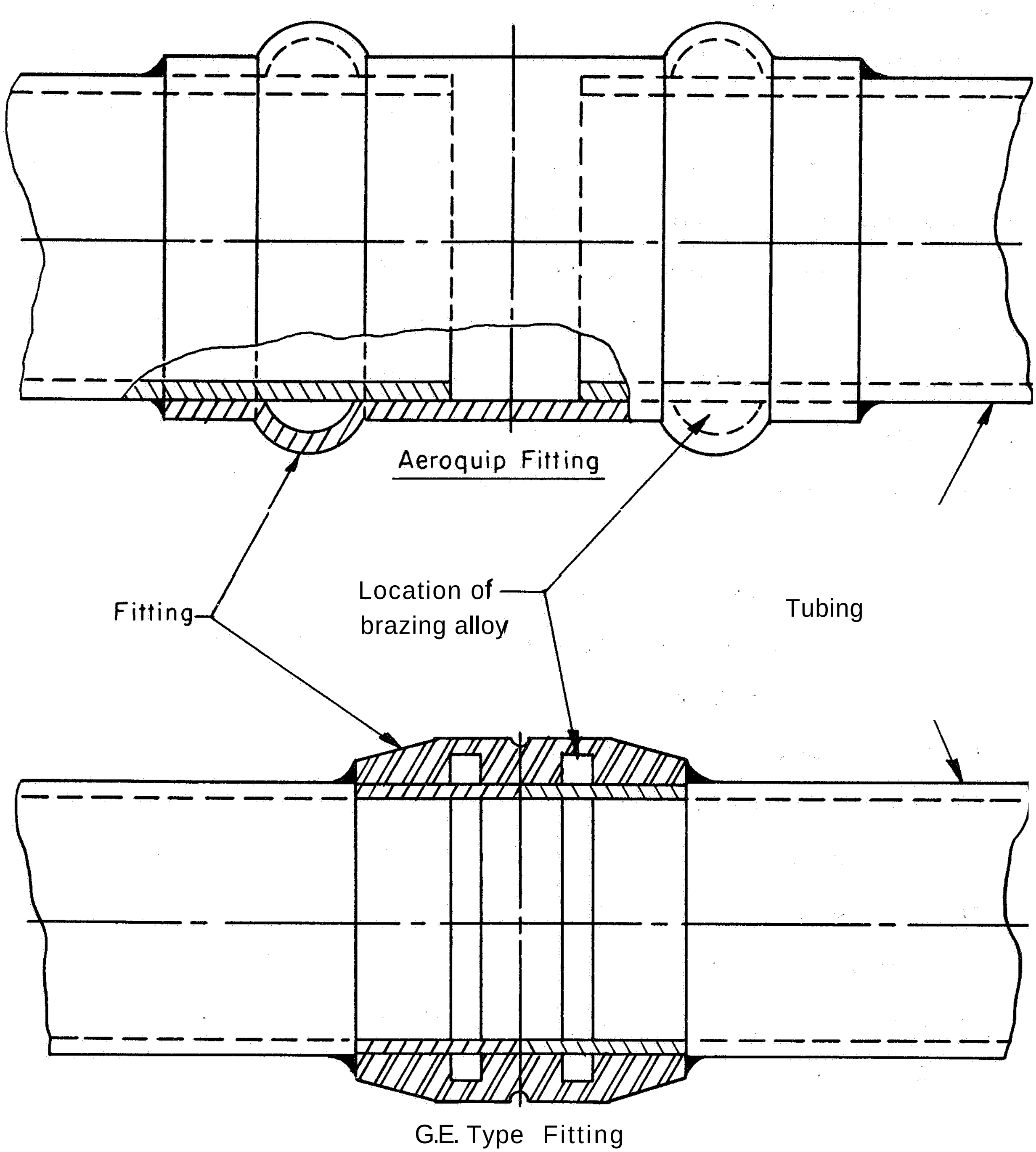


FIGURE 33. FITTINGS USED IN INDUCTION BRAZING OF STAINLESS STEEL TUBES (Ref. 79)

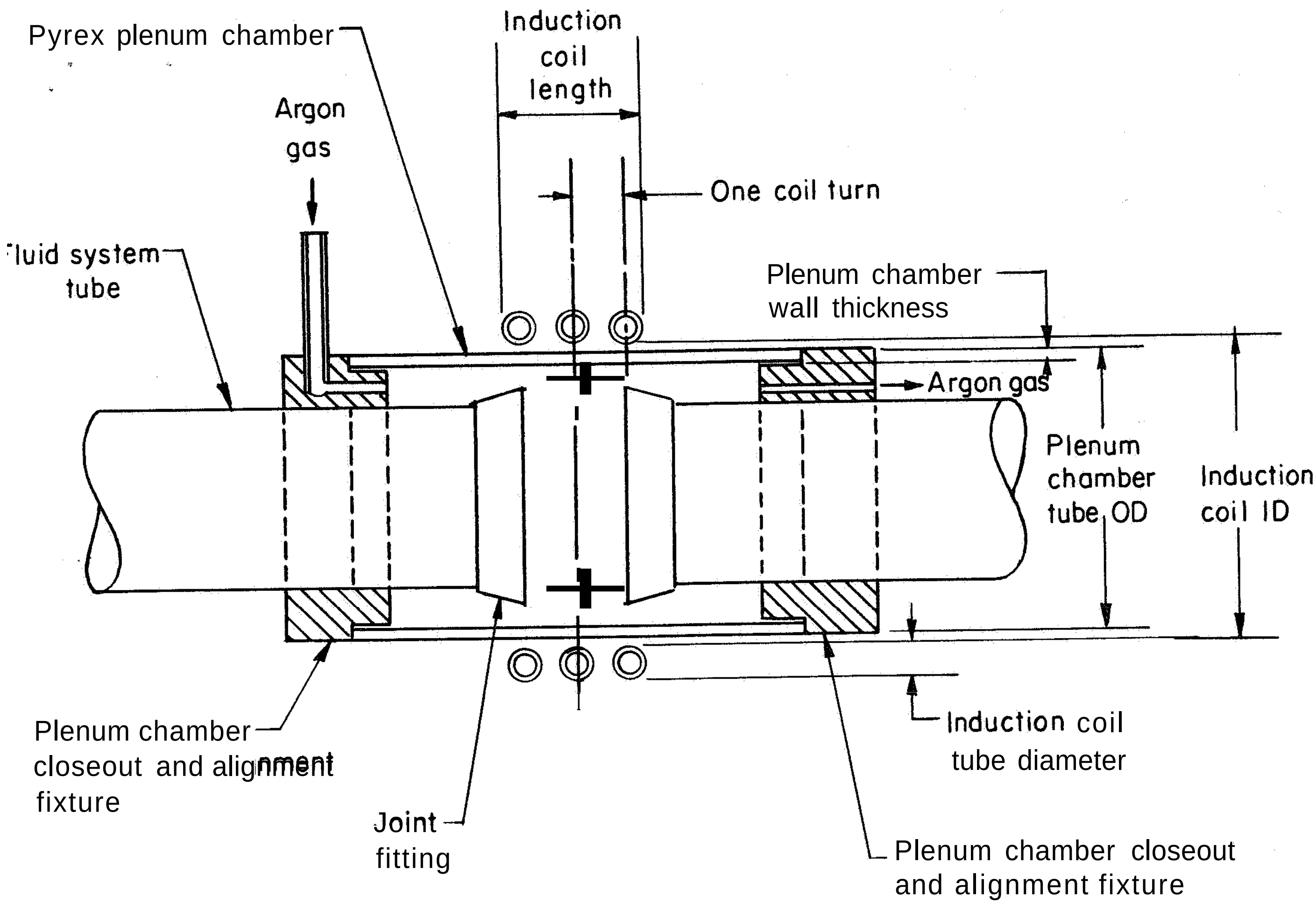


FIGURE 34. SCHEMATIC SET-UP OF TOOLING FOR INDUCTION BRAZING OF STAINLESS STEEL TUBING (Ref. 78)

(8) Initiate brazing cycle (the steps in the brazing cycle sequence automatically).

(9) Remove tool, allow joint to cool and inspect.

Details of these fabrication procedures are discussed in Reference

Induction brazed joints in tubing have met various qualification test requirements (Ref. 80). These tests have included bursting at temperatures ranging from -320 F to 1000 F, tensile tests, leak tests, shock tests, and radiographic examination. Investigations at NASA have shown that if the induction current has too high a frequency, heating is concentrated on the outer surface. This in turn results in excessive joint clearance due to nonuniform expansion of the joint fitting (Ref. 81).

Brazing is used to join stainless steel components of vacuum systems. Sound, vacuum-tight joints can be brazed readily between stainless steel tubing, bellows, and fittings providing certain basic design priciples are followed. These have been discussed in a manual by the U. S. Army Electronics Command (Ref. 82). If at all possible, the brazed joint should be located on the high vacuum side of the components being fabricated. This provides the shortest path between the vacuum environment and the atmosphere. Thus, if a leak should develop in the joint, it can be located more quickly and easily by the use of leak dectectors than if the leak would have a long path. Typical designs for tube to flange brazed joints are shown in Figures 35 and 36. Bellows should not be brazed directly to knife-edge flanges as there is a tendency to soften the knife edge with a resulting shorter flange life. Instead, the bellows should be brazed to an adapter as shown in the drawings.

For vacuum service, Vacuum Tube Grade (V.T.G.) brazing alloys should be specified. This grade of alloys are very high purity and have a very low partial pressure required for high-vacuum service.

Thrust chambers for liquid fueled rockets have been fabricated from Type 347

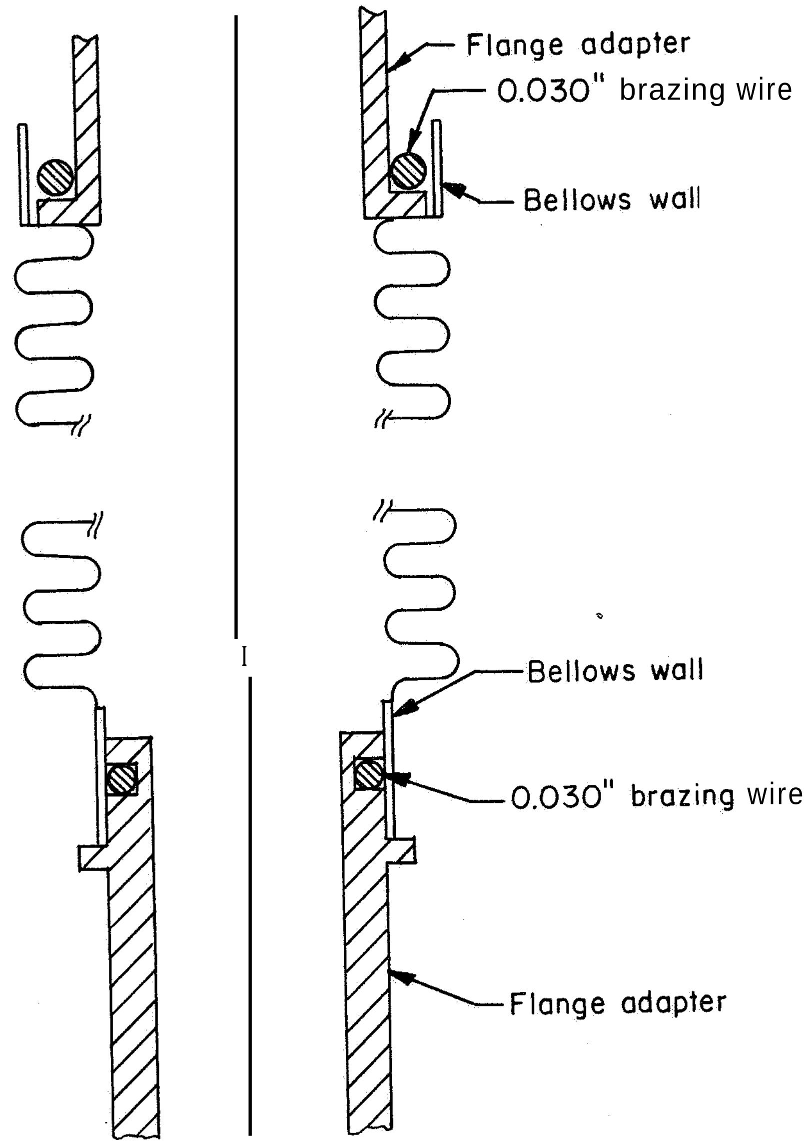


FIGURE 35. TYPICAL JOINTS USED FOR BRAZING STAINLESS STEEL BELLOWS TO FLANGE ADAPTERS FOR VACUUM SERVICE (Ref. 82)

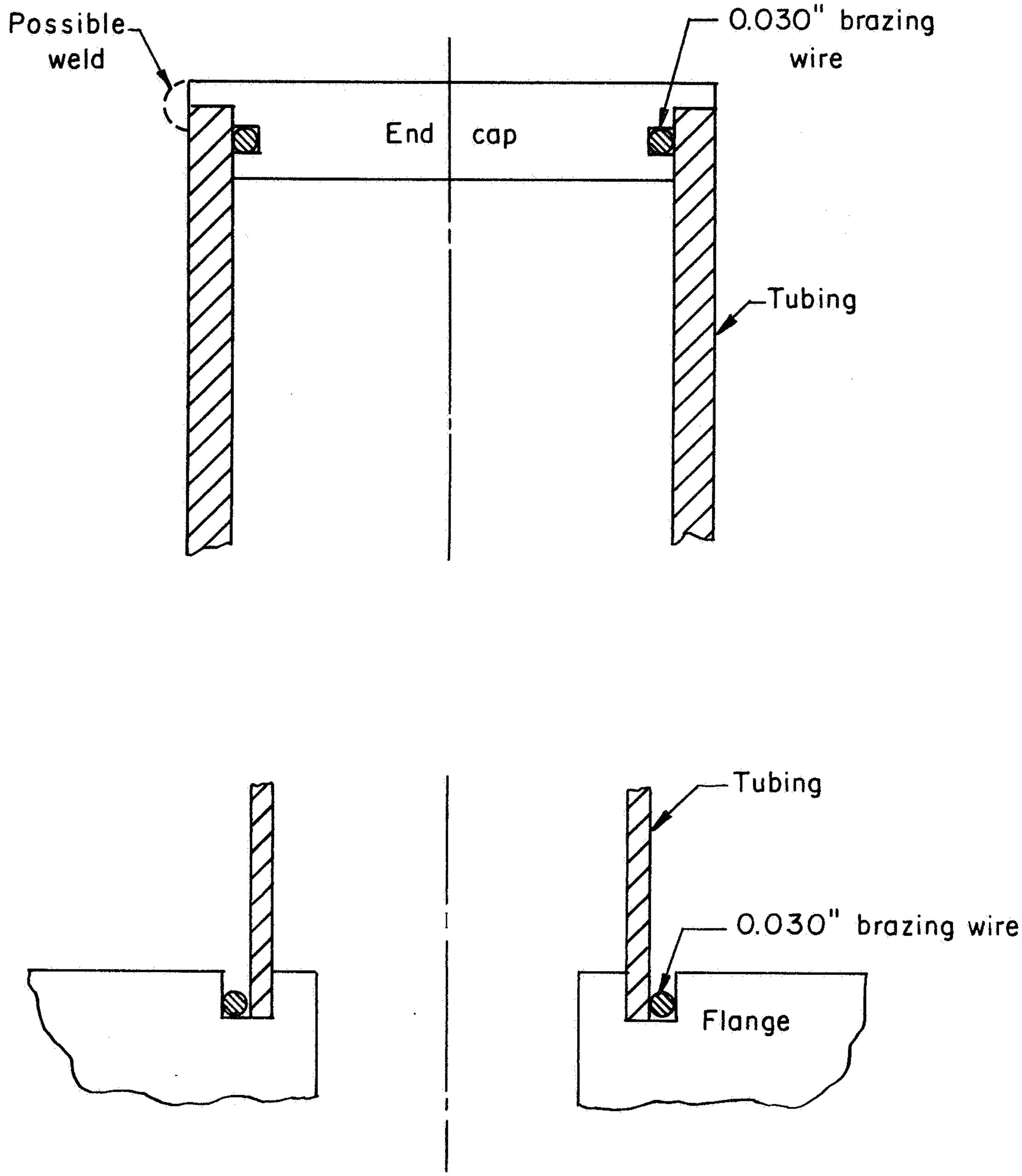


FIGURE 36. TYPICAL BRAZED JOINTS BETWEEN STAINLESS STEEL TUBING AND FLANGES AND END CAPS FOR VACUUM SERVICE (Ref. 82)

stainless steel tubes brazed together (Ref. 83). A typical thrust chamber is shown in Figure 37. The tubes are assembled on a mandrel with powdered brazing alloy applied to the tube-to-tube interface. The assembly then is sealed in a retort purged with dry hydrogen or inert gas and heated to brazing temperature in a furnace. Various nickel-base brazing alloys are used in this application. The nickel-base alloys have good compatibility with the rocket fuel, they melt either at a single temperature or over a narrow temperature range, and wet and flow freely. Some nickel-base brazed joints are brittle and may have cracks through a portion of the joint. These joints serve primarily as seals between the tubes rather than as structural joints so cracking is not a serious problem. Under proof testing and firing, these cracks do not seem to propagate,

SOLDERING

Stainless steel is rather difficult to solder because of the chromium oxide film present on the surface of stainless steels. However, if the proper measures are taken to remove this film, leak-tight joints can be soldered. It must always be remembered, though, that soldered joints are inherently weak unless an auxiliary joining method is used to obtain the desired strength. Strong joints can be obtained by spot welding, riveting, or lock rolling the seam. The soldering operation then is used to seal the seam.

The surfaces of the parts to be joined must be cleaned by degreasing. If the parts have a smooth polished finish, they should be roughened by filing, abrading with emergy cloth, grinding, or etching in a hydrochloric acid solution. The solder will adhere more readily to a roughened surface than a polished surface.

Any of the conventional soldering heat sources may be used. Commercial fluxes are available for soldering stainless steel. These fluxes are more active than the fluxes used for carbon steel. The recommended alloy to use for soldering

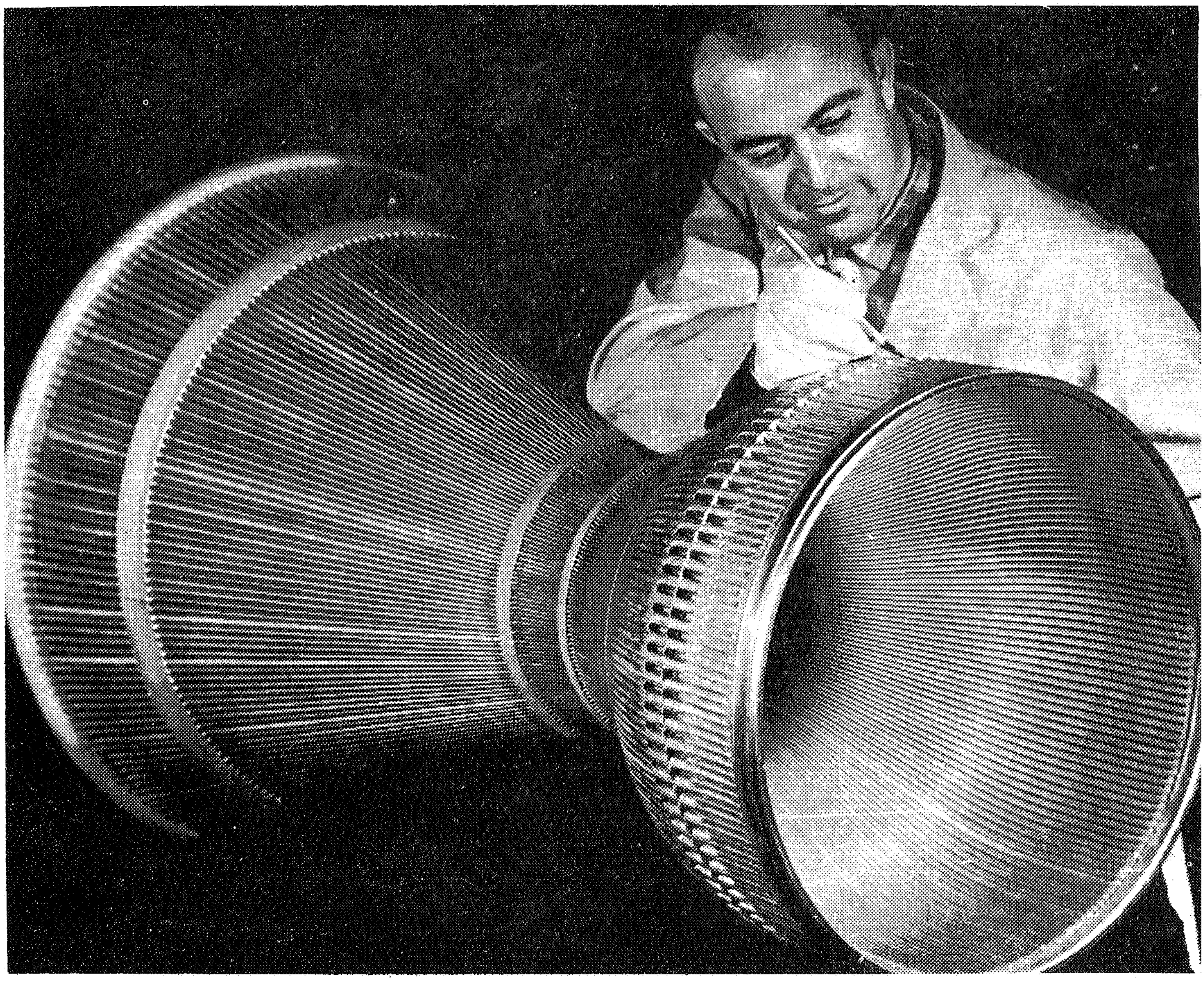


FIGURE 37. BRAZED ROCKET MOTOR THRUST CHAMBER OF TYPE 347 STAINLESS STEEL (Ref. 77)

stainless steel is 70 tin-30 lead. However, any tin-lead solder containing at least 50 percent tin can be used. Solder alloys with less than 50 percent tin since they have lower wettability and do not flow into the joint as readily. For best results, the surfaces to be joined should be tinned in advance to improve the flow of the solder.

After soldering, all flux residues should be removed with water as these are highly corrosive and can cause pitting of the stainless steel.

DISSIMILAR METALS

Occasionally, there is a need to join two different types of stainless steel together, to join a stainless steel to a low-alloy steel or carbon steel, or to overlay weld a carbon or low-alloy steel with a stainless steel deposit to provide corrosion protection. Arc welding, brazing, and diffusion bonding have been utilized in making these joints.

The difficulties which may arise when joining dissimilar metals depend mainly on the composition difference between the metals to be joined. If the compositions are similar, as in the case of two types of 300-series stainless steels, problems are relatively minor. If the compositions are radically different, as joining aluminum to stainless steel, specialized techniques must be used to avoid serious problems. The problems stem from the mixing of the two different metals during joining, particularly in arc welding. If the metals differ widely in composition, brittle phases may form in the weld metal. These weld joints may crack or will have inferior mechanical properties,

Mixing of the two metals must be minimized to produce acceptable weld joints. In arc welding, mixing of the two base metals and the filler metal is a natural result of the penetration of the base metals by the welding arc. Normally, there is less penetration and melting of the base metal with shielded metal-arc or short-circuiting GMA welding than with the other arc-welding processes. Penetration can be kept low by directing the welding arc at the weld puddle instead of at the unmelted base metal, avoiding weaving, and keeping the current as low as practical. Careful selection of the welding electrode or filler wire should be exercised. Filler metals for welding various combinations of stainless steels were listed in Table IX. In welding either a chromium-nickel or a chromium stainless steel to a carbon or low-alloy steel or to each other, best results usually are achieved using a Type 309 or 312 electrode or filler metal. Type 310 filler also is used occasionally. However, dilution of the weld metal by the carbon or low-alloy steel base metal may produce a crack-sensitive weld-metal composition due to a very high ferrite content. The Schaeffler diagram should serve as a guide in selecting a filler metal that will produce a weld metal with a low-ferrite content, It may even be advisable to use a fully austenitic electrode, such as Type 310, to prevent the formation of a hardenable weld metal or excessive amounts of ferrite (Ref. 10).

Base-metal dilution can be controlled by using a buttering technique. The joint face of the carbon or alloy steel is buttered with a layer of stainless steel before the joint is welded (Figure 38). Welding conditions for the buttered layer are selected to minimize dilution. The joint is completed in the regular manner using an electrode or filler wire that is compatible with the stainless steel base metal.

A copper-nickel electrode, E4N1A, has been used for stainless steel-carbon steel welding (Ref. 10). The weld metal that is produced can tolerate considerable dilution without cracking or developing inferior mechanical properties.

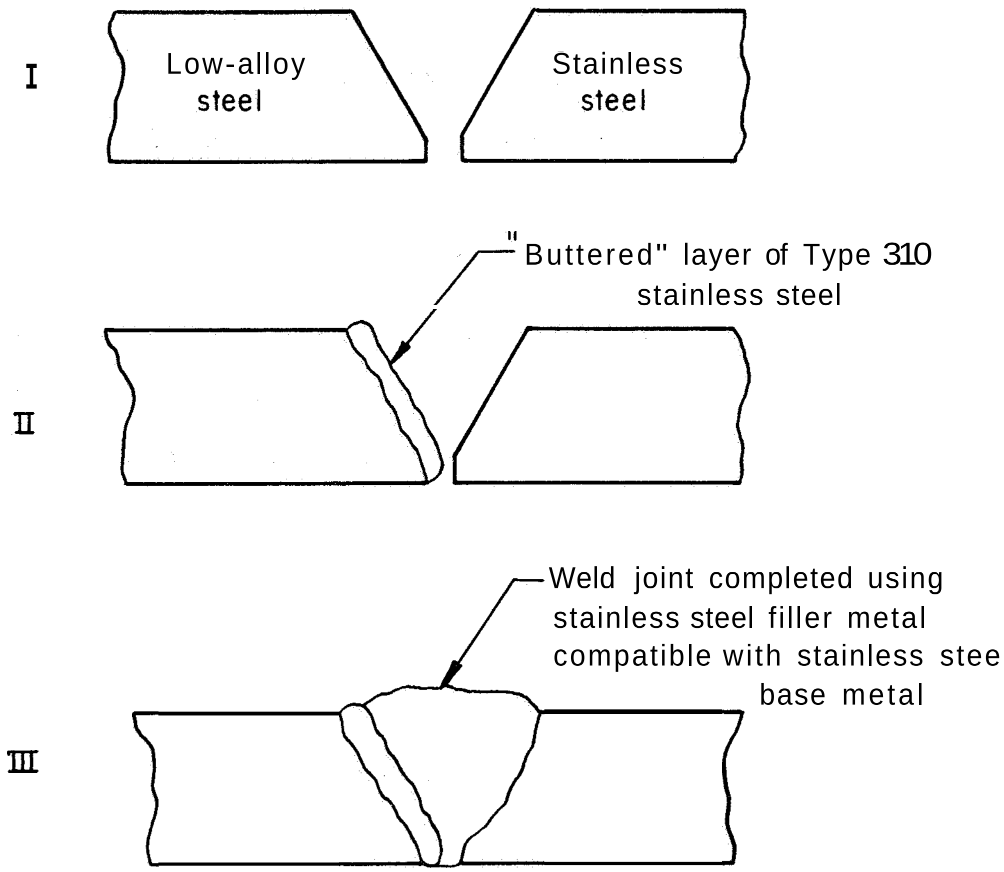


FIGURE 38. WELDING STAINLESS STEEL TO LOW-ALLOY STEEL USING "BUTTERING" TECHNIQUE

The low-alloy steel that is welded to the stainless steel may require post-weld heat treating to develop its best properties. For example, an annealing treatment in the 1250-1300 F range may be necessary to restore ductility and impact resistance to the alloy steel. Heating in this temperature range, however, impairs the corrosion resistance of the stainless steel. Heating to much higher temperatures may cause transformation and subsequent hardening of the alloy steel. A compromise is to anneal for about an hour at 1300 F (Ref. 84).

Increasing interest is being shown in the joining of stainless steel to aluminum particularly for rocket-fuel systems and military vehicle application. Frankford Arsenal developed procedures for arc welding carbon steel to 2024 aluminum that could be adapted to joining stainless steel to aluminum (Ref.85). The steel was precoated with aluminum (aluminum zinc), tin (galvanizing), or silver-brazing alloy. Butt and T-joints were made by GTA welding using aluminum-12 percent silicon filler wire. The arc was directed at the aluminum to prevent melting of the steel.

Stainless steel can be welded to nickel-base superalloys using Hastelloy X filler wire (Ref. 86). Hanford Laboratories studied the joining of Type 316, 316L, and 347 stainless steel pipe to Hastelloy X and C and Haynes Alloy 25 by GTA welding. With Hastelloy W filler wire, sound weld joints were produced providing the joints were not restrained and welding conditions were selected to minimize heat buildup in the joint area.

Brazing is an excellent method of making joints between stainless steel and other metals. Since melting of the base metal does not occur in brazing, the base metals cannot mix. However, the brazing alloy must be one that achieves good bonding with both metals. Another very important factor to be considered when brazing dissimilar metals is the difference in thermal expansion of the two metals. Joints must be designed so that the clearance between parts at brazing temperature will promote capillary flow of the brazing metal. The nomograph, Figure 39, will assist in calculating the proper clearances. The coefficients of expansion of some metals and alloys of interest are given in Table XXXIV. The useful brazing filler metals were given in Tables XXXII and XXXIII.

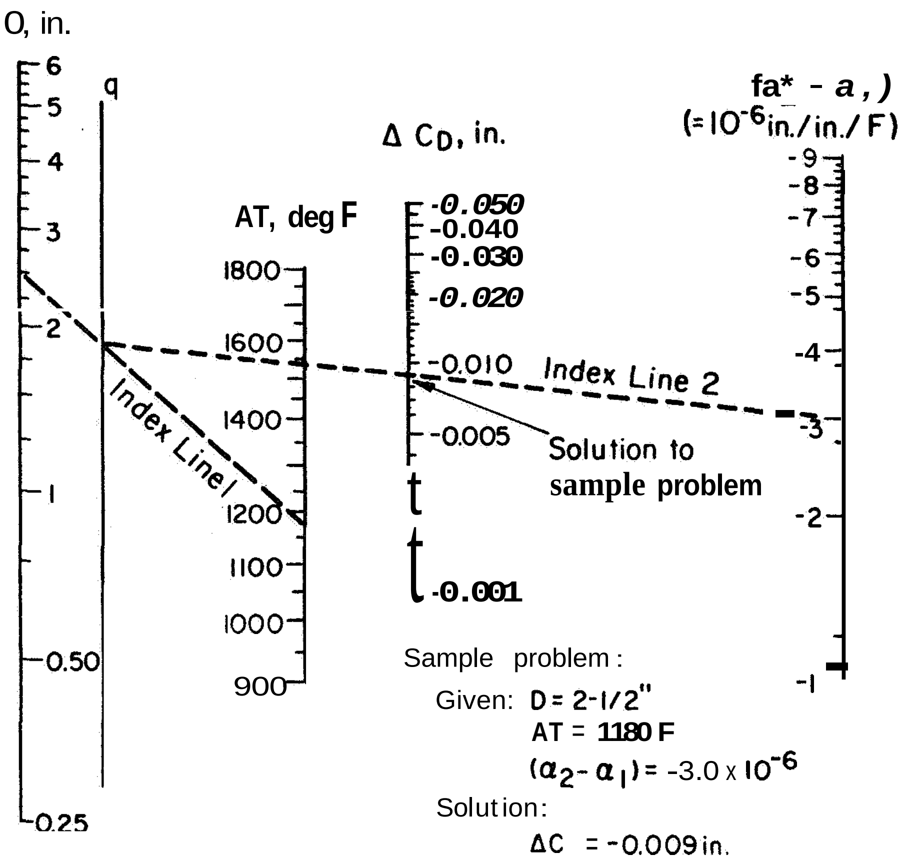
Corrosion resistance should also be an important consideration when choosing the joint design and brazing filler metal for dissimilar metals joints. The subject is too complex for coverage in this report. Corrosion handbook data are not always directly applicable to brazed assemblies due to the dissimilar metal corrosion couples involved. Unless directly relative data are available, laboratory studies should be used to establish the feasibility of a particular joint system in a particular corrosive environment.

North American Aviation developed techniques for brazing Type 304L stainless steel to 6061 aluminum (Ref. 87). The purpose of this joining operation is to join stainless steel tubing to aluminum tubing for a space vehicle liquid propellant system. The steps involved in this operation are:

(1) The stainless steel is tinned with an electroless nickel plate followed by an electrolytically deposited tin coating of 0.0001 to 0.0003 inch thickness.

(2) The aluminum is cleaned immediately prior to brazing by hot alkaline and mixed deoxidizer bath.

(3) The joint is assembled. A telescoping-type joint is used with the aluminum on the outside. By having the aluminum alloy with its higher thermal expansion on the outside, brazing can be done without inducing thermal stresses in the joint. Joint clearance is 0.001 to 0.004



NOTES:

(1) This nomograph gives change in Uiameter caused by heating. Clearance to promote brazing filler metal flow must be provided at brazing temp.

(2) D = nominal diameter of joint, inches
C_D = change in clearance, inches
T = brazing temp minus room temp, F
α_1 = mean coefficient of thermal expansion, male member, in./in./deg F
α_2 = mean coefficient of thermal expansion, female member, in./in./deg F

(3) This nomograph assumes a case where α_1 exceeds α_2, so that scale value for $(\alpha_2 - \alpha_1)$ is negative. Resultant values for ΔC_D are therefore also negative, signifying that the joint gap reduces upon heating. Where $(\alpha_2 - \alpha_1)$ is positive, values of ΔC_D are read as positive, signifying enlargement of the joint gap upon heating

FIGURE **39.** **NOMOGRAPH** FOR **FINDING THE CHANGE IN** DIAMETRAL **CLEARANCE IN JOINTS** OF **DISSIMILAR METALS** FOR **A VARIETY** OF BRAZING **SITUATIONS** (Ref. 77)

TABLE XXXIV. COEFFICIENT OF THERMAL EXPANSION OF SOME COMMON ALLOYS

Alloy	Coefficient of Expansion (32-212 F) 10^{-6} in/in/F
Type 302 stainless steel, annealed and cold rolled	8.0
Type 304L stainless steel, annealed	8.0
Type 321 stainless steel, annealed and cold rolled	8.3
Type 410 stainiess steel, annealed and heat treated	5.1
AM 350, sol. treated and hardened	6.8
15-7Mo, Condition TH 1050	6.1
17-7 PH, Condition TH 1050	6.i
A 286, sol. treated, quenched 'and aged	9.4
AISI 4340 steel, annealed	6.3
AISI 1020 steel, annealed	6.5
René 41	7.5
Inconel, annealed	6.4
Inconel X, annealed	7.6
Nickel	7.2
Aluminum	13.1
Tungsten, sintered	2.2
Molybdenum, 1/2% Ti, stress relieved	3.4
Tantalum, annealed	3.6
Columbium, annealed	4.0
Titanium, commercially pure	4.7

inch for 1/4- to 1-inch diameter tubing and 0.001 to 0.006 for 1-to 3-inch-diameter tubing.

(4) A ring of brazing alloy, 718 aluminum, is preplaced in the joint.

(5) The assembly is preheated to 400 to 900 F and then salt-bath brazed. The preheat temperature depends on the size of the assembly compared to the size of the salt bath. After brazing, the assembly is cooled in air or water spray and then cleaned of all residual salt.

For some dissimilar metal combinations there may not be any usable brazing alloy. In these situations, diffusion bonding has been used with good success. The Boeing Company developed procedures for diffusion bonding thin-walled Type 321 stainless steel cylinders to 2219 aluminum cylinders (Ref. 88). This application is same as that for which stainless steel was brazed to aluminum by North American Aviation (rocket-fuel propulsion system). However, brazing could not be used in this case because no suitable brazing alloy is available that can be used for dip brazing 2219 aluminum. 6061 aluminum could be used as a transition ring between the 2219 and stainless steel. This technique is satisfactory for small-diameter tubing. The application in question, however, was for very large diameter (20 to 50 inch) pipes and the tooling problems were excessive. The diffusion-bonding procedure that was developed is applicable to both large and small diameter parts.

For bonding, both the stainless steel and aluminum are silver plated (0.0004 to 0.0005 inch thick). The stainless steel and aluminum then are assembled over a stainless steel mandrel (Figure 40). A low-alloy steel ring is shrunk fit over the assembly. For bonding, the entire setup is heated to 500 F for 2 to 4 hours. The difference in thermal expansion of the stainless steel mandrel and the low-alloy steel ring squeezes the stainless steel and aluminum together at the joint. (The stainless steel mandrel expands more than does the low-alloy steel ring.) The combination of the squeezing pressure (20 to 25 ksi) and

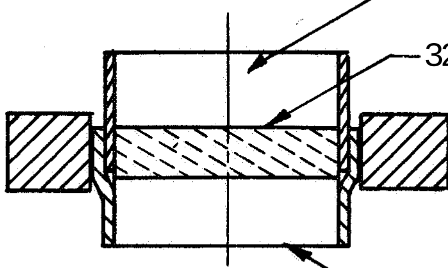


FIGURE 40. DIFFERENTIAL THERMAL EXPANSION TOOLING FOR DIFFUSION BONDING OF STAINLESS STEEL TO ALUMINUM (Ref. 88)

the high temperature affects a diffusion bond between the stainless steel and aluminum. Twenty-inch diameter joint assemblies successfully passed cyclic pressure tests at room temperature and -320 F and exhibited burst test pressures up to 670 psig at -320 F. This burst pressure is equivalent to a hoop stress of 53,600 psi which exceeds the yield strength of the aluminum alloy at -320 F.

JOINT QUALITY

Stainless steels are high-quality materials and it is essential that welds made in these alloys be of high quality. Stainless steels are selected for use because of their superior corrosion resistance, heat resistance, appearance, strength, toughness, or formability. If the end product is to meet these requirements and perform satisfactorily in service, the weld must be of adequate quality.

INSPECTION

Stainless steel weldments are inspected both destructively and nondestructively. Nondestructive inspections are almost always performed, but destructive inspection generally is performed only occasionally on completed product joints. It is often necessary and desirable to check changes in dimensions that may have resulted from welding. The visual- and measurement-type inspections performed for this purpose may also include checks of weld-joint profile and measurements of the weld thickness. Various inspection procedures also are used to insure that the joints produced are of satisfactory quality. The most commonly used techniques in this area include visual, dye penetrant, and X-ray techniques. Various types of leak tests are also used on components designed to contain gases or fluids.

DEFECTS IN ARC WELDS

The definition of joint defects is arbitrary. Many years of experience have been gained with welding codes and specifications that either prohibit or allow certain features characterized as defects. Features recognized as defects are generally limited in accordance with conservative practices. This appraach to defects has been quite successful in the past, but is of some concern when dealing with many of the newer materials being used in various types of fabrication. This concern is based on the belief that the removal of certain types of features classified as nonallowable defects often results in more damage to the serviceability of a structure than the damage that potentially might have been done by allowing the feature to remain. The reluctance of many welding engineers to repair certain features is based on this feeling, not on a desire to make the welding job easier.

The fabrication of defect-free welds is highly dependent on the quality requirements of applicable specifications and on the inspection methods that are used. However, cracked welds can and do get into service if inspection methods that will insure detecting all cracks present in a weld are not required and used.

The only reliable way to determine what weld features are truly defects is to evaluate the effects of such features in a test program. Such an evaluation must include tests that are representative of the service conditions. Many defect-like weld features have no effect on the static-tension properties of the weld. However, these same features may be found to degrade performance seriously in a fatigue test.

With the knowledge currently available about the performance of fusion weldments, a conservative engineering approach to defects should be followed.

The chief causes of poor weld quality are: porosity, cracking, improper penetration, and poor bead contour (Figure 41). For stainless steels, care also must be taken to insure that the joint has satisfactory corrosion resistance. Some defects can be traced to poor welding practices while others are caused by such things as improper jigging, poor joint design, damp electrodes, and poor cleaning practices.

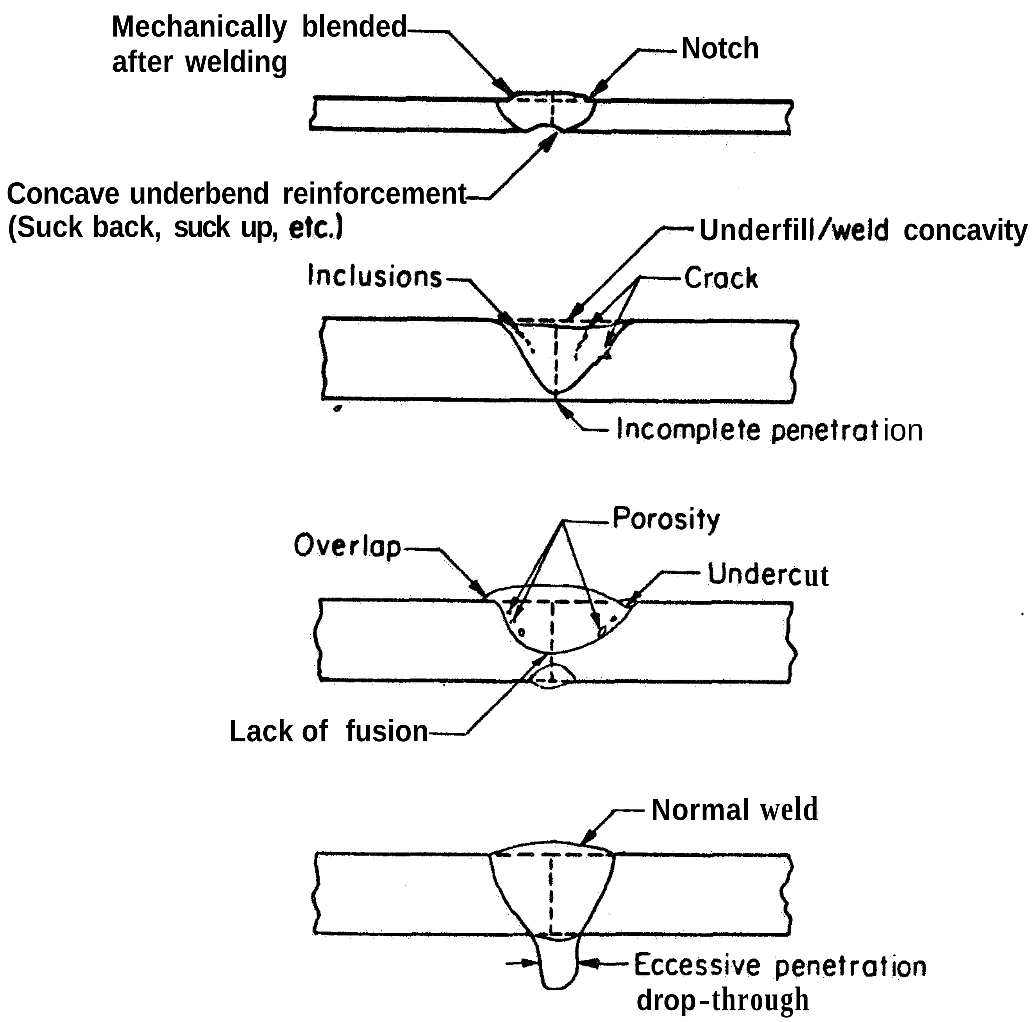


FIGURE 41. ARC-WELD DEFECTS

Porosity. Porosity in stainless steel welds is caused primarily by dirt and grease on the parts being welded or on the electrode. The heat from the welding arc vaporizes these materials and the vapor produces gas pockets as the weld metal solidifies. All parts should be clean before welding. This includes tools, jigs, or even the operator's hands or gloves.

Welding practices that result in poor shielding of the arc and molten weld puddle also cause porosity. In shielded metal-arc welding, poor shielding can occur if the electrode is at the wrong angle or the arc is too long. In the inert-gas shielded processes, the wrong position, improper flow of shielding gas, or drafts can disrupt the gas shield.

Cracking. The cracking of weld joints is the most serious defect that can occur in the welding of any metal, stainless steel included. Cracked welds are weak. Cracks on the surface of stainless steel welds exposed to corrosive liquids are good locations for corrosion to start.

Cracking may occur in the weld metal. Cracks may vary in size from microscopic to gross cracks easily seen by the unaided eye. Weld-metal cracking usually may be traced to metallurgical causes and the selection of the proper filler metal composition does much to minimize this problem. This is particularly true when balancing the weld-metal ferrite content. Foreign matter that can introduce sulfur into the weld metal can cause cracking (Ref. 17,18). Still another source of cracking is copper that might be picked up from a backup bar or hold-down clamp.

Cracking in the heat-affected zone of the weld joint usually is a characteristic of the particular base-metal composition being used. These cracks are a result of a combination of the loss of ductility of the base metal due to the thermal cycle and the strains imposed by heating and cooling. This type of cracking is minimized by changing the welding procedure (decreasing the size of the weld pass), removing external restraint on the weld joint, or, sometimes by changing the weld-metal composition. Preheating when welding the hardenable stainless steels also is helpful.

Improper Penetration. This can mean not enough penetration (incomplete penetration) or lack of fusion, or too much penetration (excess penetration). A weld joint that does not have enough penetration is not getting enough welding heat. This usually means that the current is too low or the travel speed is too high. The converse is true when excessive penetration occurs, The location of the arc with relation to the molten puddle and the position of the electrode also influence the amount of penetration that is obtained.

Poor Bead Contour. The shape or contour of the weld bead can be affected by incorrect welding conditions. Undercut and overlap are particularly serious in stainless steel welds. Both of these conditions leave a crevice or notch which is a good place for corrosion to start, particularly if the weld is under load at the same time. The notch that is formed also is a stress raiser that could cause failure of the joint at relatively low loads.

Poor Corrosion Resistance. Carbide precipitation is the most frequently encountered cause of poor corrosion resistance in stainless steel welds. This problem was discussed in the section on Metallurgical Factors in the Welding of Stainless Steel. Carbide precipitation is related to the carbon content of the weld metal. Enough carbon can be picked up from dirt, grease, and other foreign matter to cause carbide precipitation, even in the low-carbon or stabilized grades of stainless steel.

Stress corrosion may be encountered if the weld joint sees service in certain environments, particularly one that contains chloride. The weld joint must be under stress for this type of corrosion to occur. Joint designs and welding procedures that minimize residual stresses are helpful in preventing this type of corrosion.

A weld joint that has incomplete penetration, undercut, protrusions, or other surface discontinuities such as backing rings or excessive penetration may be subject to crevice corrosion, Foreign material can collect in these discontinuities and isolate the surface of the stainless steel from the surrounding environment. In a fluid environment, a difference in concentration of the fluid or oxygen content may be created between the isolated surface and other exposed surfaces of the stainless steel. These differences will cause' anodic and cathodic areas to be formed with subsequent corrosive attack in the crevice (Ref. 11). This is known as crevice corrosion.

DEFECTS IN RESISTANCE WELDS

Characteristics described as defects in resistance welds are difficult to assess. Defects in resistance welds are generally subdivided into external and internal defects. With the exception of cracks that are exposed to the exterior of the sheets and that are obviously undesirable, the remaining external defects are probably considered as such because they are indicative 'that the welding conditions may not have been exactly right. External defects in this category are sheet preparation, surface pits, metal expulsion, tip pickup, and excessive indentation. With internal defects, cracks are obviously undesirable, but there is very little evidence that porosity in minor amounts is harmful to properties. The same is true of either insufficient or excessive penetration. Typical defects in resistance spot and seam welds and their causes are given in Figure 42 (Ref. 89).

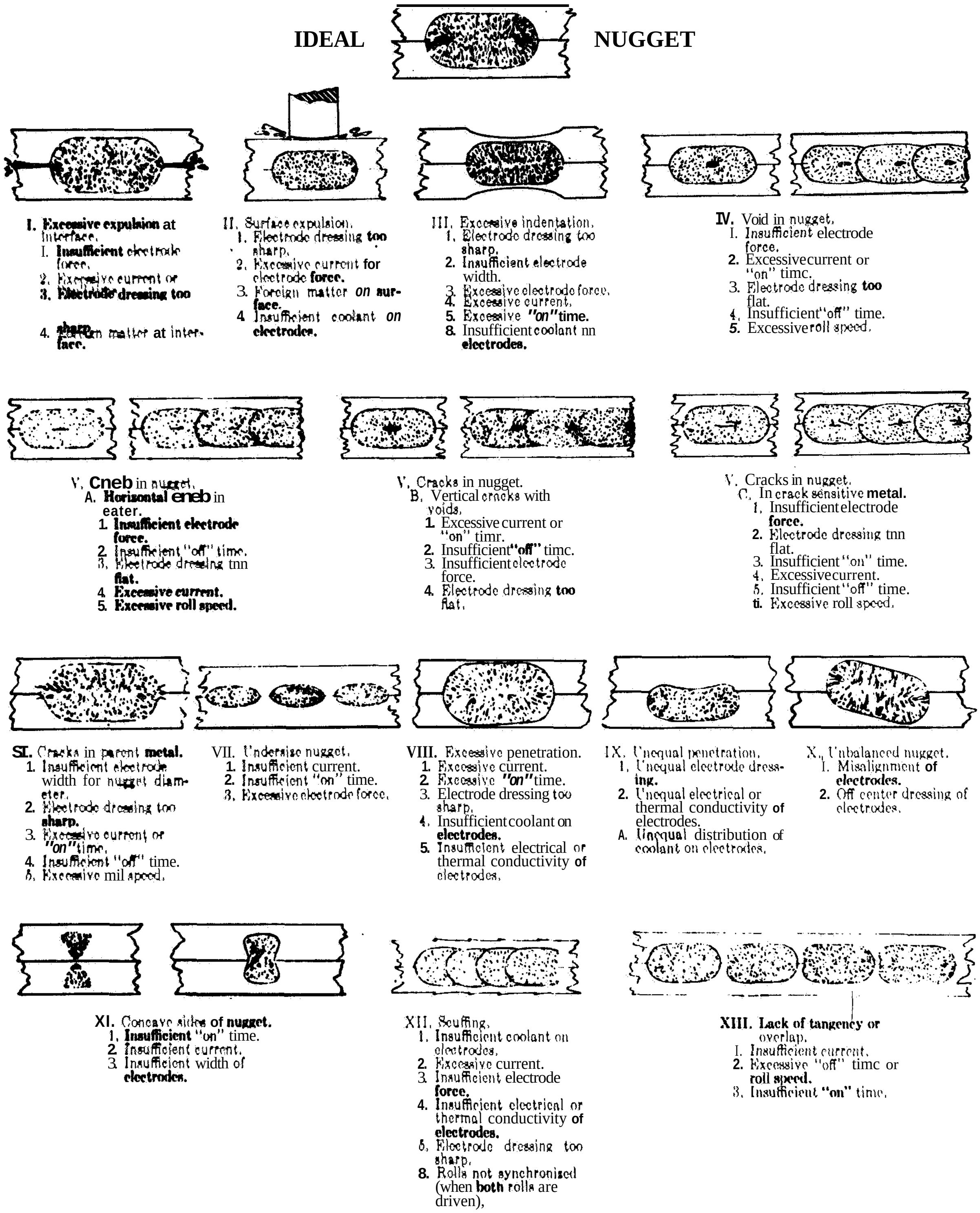
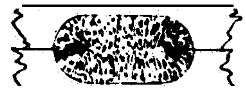
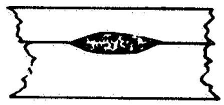


FIGURE *42.* COMMON DEFECTS IN RESISTANCE-SPOT AND SEAM WELDS AND THEIR CAUSES (Ref. 85)
(Prevalent causes in order of importance)
Courtesy of Allegheny Ludlum Steel Corporation.

IDEAL  **NUGGET**

I. Lack of penetration in thin sheet.
1. Electrode dressing too flat on thin sheet.
2. Excessive electrode force.
3. Excessive electrical or thermal conductivity of electrode on thin sheet.
4. Insufficient electrical or thermal conductivity of electrode on heavy sheet.

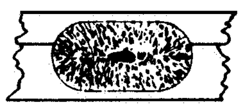


II. Lack of penetration in both sheets.
1. Electrode dressing too flat.
2. Excessive electrode force.
3. Insufficient current.
4. Insufficient "on" time.

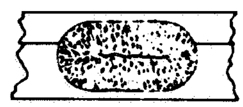
III. Unbalanced nugget.
1. Misalignment of electrodes.
2. Off-center dressing of electrode faces.

IV. Excessive indentation.
1. Electrode dressing too sharp at indentation.
2. Excessive electrode force.
3. Excessive current or "on" time.
4. Insufficient width of electrode at indentation.

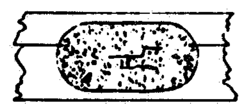
V. Excessive penetration.
1. Electrode dressing too sharp on thin sheet.
2. Insufficient electrode force.
3. Excessive current or "on" time.
4. Insufficient electrical or thermal conductivity of electrode.
5. Insufficient coolant.



VI. Void in nugget.
1. Insufficient electrode force.
2. Excessive current.
3. Excessive "on" time or roll speed.
4. Electrode dressing too flat.
5. Insufficient "off time.



VII. Cracks in nugget.
A. Horizontal cracks at center.
1. Insufficient electrode force.
2. Insufficient "off" time.
3. Electrode dressing too flat.
4. Excessive current or "on" time.



VII. Cracks in nugget.
B. In crack sensitive metal.
1. Insufficient electrode force.
2. Electrode dressing too Oat.
5. Insufficient "off" time.

VIII. Cracks in parent metal.
1. Insufficient electrode width for nugget diameter.
2. Electrode dressing too sharp.
3. Excessive roll speed.
4. Excessive current or "on" time.
5. Insufficient "off" time.
6. Insufficient electrode face.

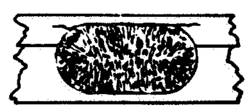


FIGURE *42.* **(Continued)**

CONCLUSIONS AND RECOMMENDATIONS

The technology of joining stainless steels has been well developed over a period of many years. Most of the problems related to joining stainless steels have been solved through extensive research efforts. At present, stainless steels can be readily joined by any of the conventional welding processes, by brazing, and by solid-state bonding. However, numerous precautions must be followed to insure high-quality joints. These precautions have generally been adopted into the standard procedures recommended for joining stainless steels.

Some aspects of joining stainless steel still require study and development. Most of these problem areas have come about through the use of stainless steels in new applications, more stringent design or service requirements for stainless steel weldments, or through the applications of new processes to the joining of stainless steel. Recommendations for areas of further study are discussed in the following sections.

WELDING CONDITIONS

In recent years, several new welding processes have been introduced into industry. These include Narrow-Gap, electroslag, electrogas, high-frequency resistance welding, and open-air and low-vacuum electron-beam welding. The performance of these processes with carbon and low-alloy steels or with various nonferrous metals indicates that they should be advantageous to use to weld stainless steels. A concentrated effort to develop procedures or materials for use with stainless steels has not been made. However, such an effort should perfect the welding of stainless steels by these processes.

SHIELDING GASES

The gas metal-arc welding process is one of the common methods of joining stainless steel. The short-circuiting method of GMA welding is being used more and more frequently. The maximum economic advantages of short-circuiting GMA welding are realized when a shielding gas with a high percentage of carbon dioxide is used. However, the weld metal picks up carbon from such shielding gases. The amount of pickup varies with the percentage of carbon dioxide and possibly the welding conditions. Investigators already have shown that the corrosion resistance of the weld joint is related to the amount of carbon pickup from the carbon dioxide in the shielding gas. Further efforts are required to develop more extensive quantitative data on carbon pickup from shielding gases containing specific amount of carbon dioxide. This in turn can lead to the establishment of limits on carbon dioxide when welding stainless steels for various service applications.

Some efforts also have been made to compensate for this carbon pickup. One approach has been to use very low carbon filler wire. Limits on wire carbon content for various amounts of carbon dioxide in the shielding gas would be desirable.

CRACKING

Numerous studies have been conducted in determining the causes of fissuring (microcracking) in stainless steel weld metal and heat-affected zones. The cause of fissuring generally is attributed to impurity segregation in grain boundaries. These studies have been limited to a few types of stainless steel and exact limits have not been set on impurity content to prevent fissuring. These studies should be expanded to determine impurity limits and if the impurity content is the same for all types of stainless steel. Fissuring is frequently encountered in columbium bearing stainless steel (Type 347). Further efforts are required to isolate the causes and cures of fissuring in the columbium bearing stainless steels.

CORROSION

Stress corrosion cracking may occur in weld joints under stress (particularly residual stress) in the presence of certain environments. Quantitative data are lacking that enable a fabricator or user to predict whether stress corrosion cracking will occur. Such data would be especially desirable since stress relieving of stainless steel (the usual solution to this problem) requires high temperatures and long times. Stress relieving is not completely reliable as residual stresses can arise again on cooling after stress relieving.

DISTORTION

Distortion is more serious with stainless steel than with carbon or low-alloy steels. Distortion can be extremely serious in large fabrications or where dimensions are critical. Little quantitative data are available on amounts of distortion to be expected from a particular part configuration, stainless steel thickness, or the use of a particular process. Such data would enable a fabricator to compensate for distortion before the weld is made.

DISSIMILAR METALS

Welds between stainless steel and carbon steel are readily made. However, problems may be encountered in thermal cycling service from stress concentrations arising from differences in thermal expansions of the stainless steel and carbon steel. Some filler metals have been developed that have intermediate thermal expansions to alleviate this problem. However, further effort in this area is required.

The joining of stainless steel to nonferrous metals is an area of growing interest. Several metal combinations have been successfully joined to date by brazing and diffusion bonding. As the need for joining additional metal combinations arises, further development work will be needed. Requirements of these joints will include both good strength and corrosion resistance.

APPENDIX A

WELDING PROCESSES

WELDING PROCESSES

Welding processes that have been used for joining stainless steels are described briefly in the following. These processes are described in considerable additional detail in the published literature (Refs. 29,92).

SHIELDED METAL ARC

Shielded metal-arc welding is usually done manually. The heat required to melt the filler metal and joint edges is produced by an arc between a covered electrode and the work. The electrode is composed of a metal rod coated with materials which when heated by the arc produce (1) a gas which shields the arc area from the atmosphere, (2) promotes electrical conduction across the arc, (3) produces slags which refine the molten pool, provide some protection from the atmosphere, and add alloying elements, and (4) provide materials for controlling bead shape. Figure A-1 is a sketch which shows the basic operation of this process.

GAS TUNGSTEN-ARC WELDING

In this process, which may be used manually or with automatic equipment, the heat to melt both filler metal and joint edges is produced by an arc between a tungsten (nonconsumable) electrode on the work. A shield of protective gas surrounds the arc and weld region. Filler metal may or may not be added to the weld. If it is, it is not normally a part of the arc circuit and is called a "cold wire" addition. The process is often called the GTA or TIG process.

Argon, helium, or a mixture of the two gases are used for shielding against the atmosphere. These gases are chemically inert, they do not react with other materials. Argon is more extensively used than helium.

Figure A-2 is a sketch of a gas tungsten-arc system.

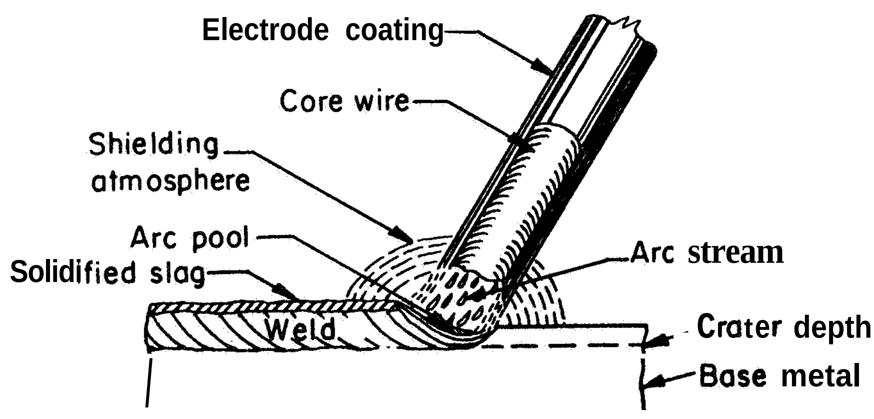


FIGURE A-1. SKETCH OF SHIELD-METAL-ARC WELDING OPERATIOH (Ref. 29)

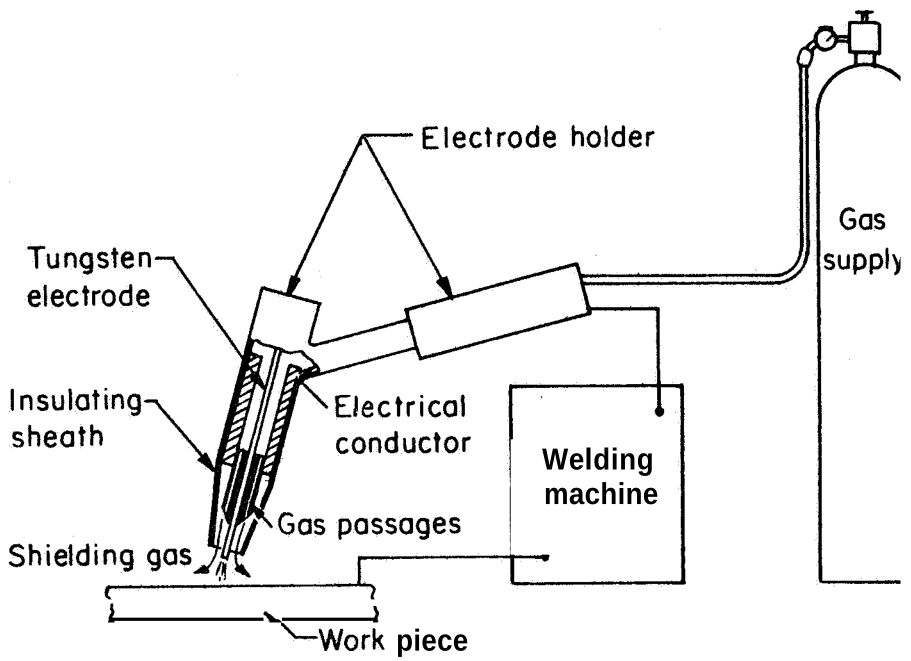


FIGURE A-2. SKETCH OF A GAS TUNGSTEN-ARC WELDING SYSTEM (Ref. 29)

GAS METAL-ARC WELDING

In this process, it is used both manually and with automatic equipment; the heat to melt filler metal and the joint edges is produced by an arc between a metal wire (consumable) electrode and the work. Arc and weld are shielded from the atmosphere by a shield of protective gas. The electrode is a small-diameter wire (about 0.035 *to* 0.065 inch diameter for stainless steel) with no coating. The process is often called the GMA or MIG process.

Argon, carbon dioxide, and their mixtures, and argon-oxygen mixtures are used for shielding gases. Argon with 1 or 2 percent oxygen is generally used with stainless steels. Figure A-3 is a sketch of a gas metal-arc welding system.

SUBMERGED-ARC WELDING

The heat to melt the filler metal and joint edges is obtained form an arc between a base-metal electrode or electrodes and the work. The arc and weld zone is shielded by a blanket of flux which covers the joint and the end of the electrode. The arc is buried beneath the flux. The flux is a granular mineral material whose composition and properties are designed to:

(1) Provide protection from the air during welding.

(2) Provide materials to deoxidize and alloy the weld metal.

(3) Provide (when melted) a conductive path for the welding current.

(4) Provide a slag which molds the surface of the weld.

Generally, an amount of flux about equal to the weight of filler wire is melted during the welding operation. It is this melted portion of the flux which accomplishes most of the actions listed above. The unmelted portion of the flux is picked up by vacuum cleaning equipment and recirculated to the weld head. Figure A-4 is a sketch which shows the details of this process.

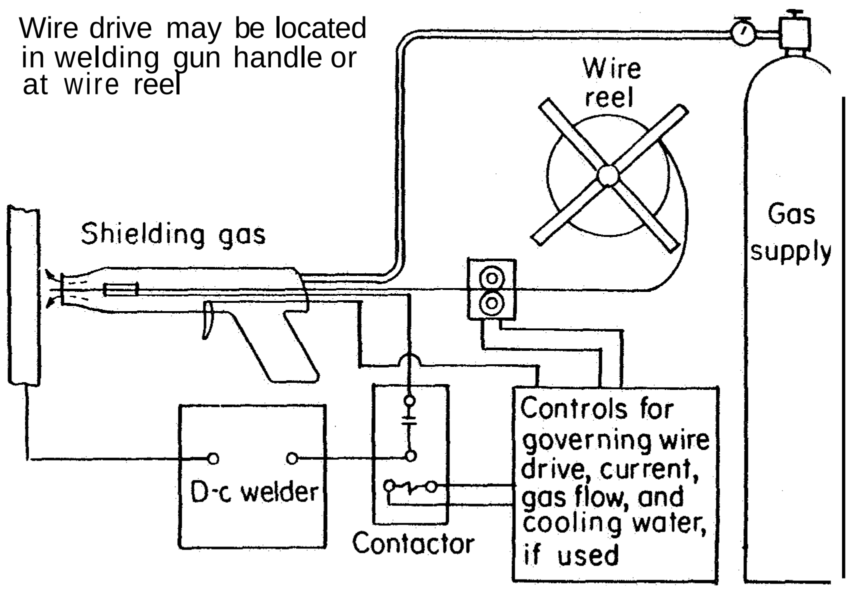


FIGURE A-3. SKETCH OF A GAS METAL-ARC WELDING SYSTEM (Ref. 29)

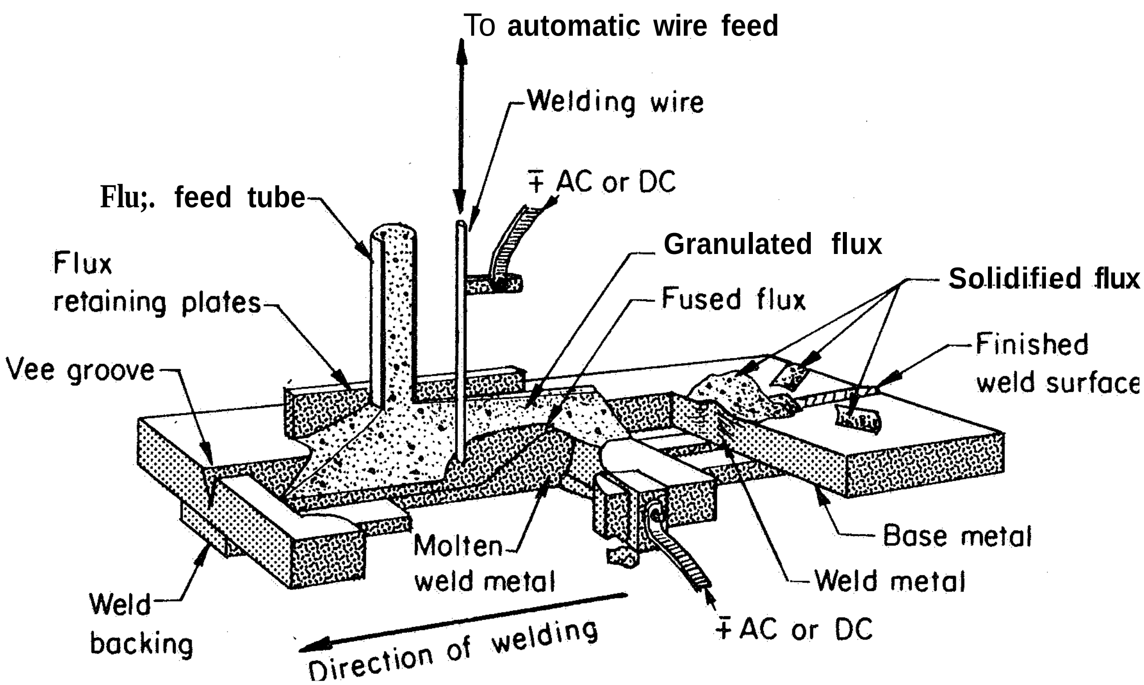


FIGURE *A-4.* SKETCH OF SUBMERGED–ARC WELDING OPERATION

PLASMA-ARC WELDING

This process melts the filler metal and joint edges by using the heat produced. by passing a gas through an arc and an orifice to produce high-temperature plasma. Welding is done using a "transferred" arc which means that the work has to be part of the welding electrical circuit. This process is a specialized adaption of the gas-tungsten-arc process. In welding, inert gases are usually used to form the plasma. An additional inert gas shield is used to protect arc, plasma, and weld from the air. The advantages of the process over gas-tungsten-arc welding are:

(1) Higher energy concentration

(2) Improved arc stability

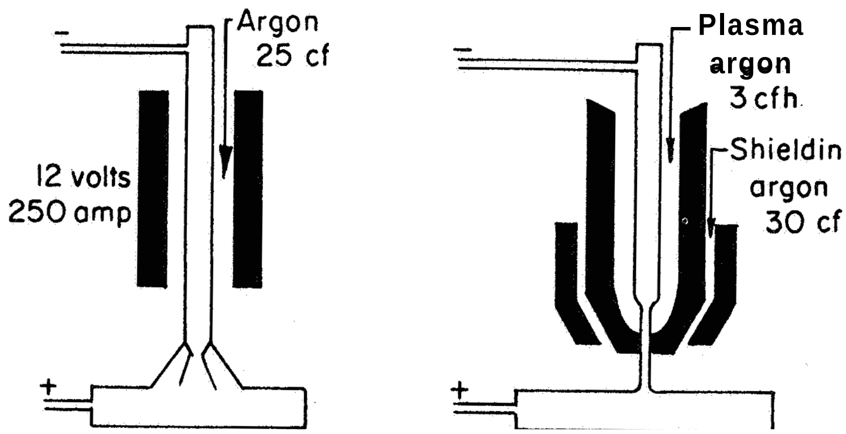
(3) Higher energy transfer.

Using certain gas flow and electrical power settings the arc plasma torch can be turned into an effective cutting tool. Plasma cutting is particularly effective with stainless steels since it does not depend on oxidation to facilitate cutting. Figure A-5 is a sketch of a plasma-arc system.

ELECTRON-BEAM WELDING

This is a fusion-welding process which does not use an arc as a heat source. The work is bombarded by a high-energy, high-density stream of electrons. Practically all of the electron energy is transformed into heat when the electrons impact the work. As originally developed, electron-beam welding was done in an evacuated chamber. In about 1963, some capability for welding at pressures up to atmospheric was developed. While this loses the advantage of the high-purity atmosphere which the vacuum represents, it increases the adaptability of the process.

One outstanding feature of electron-beam welds is the very narrow welds (high depth-to-width ratio) that can be made with the process. It is possible to produce



a. Comparison Gas-Tungsten Arc and Plasma Torch

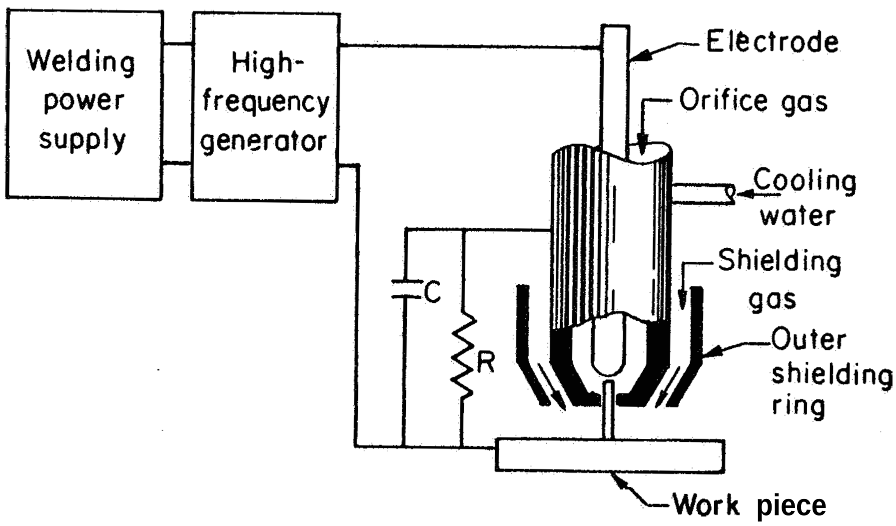


FIGURE A-5. SKETCH OF PUSMA-ARC TORCH AND SYSTEM (Ref. 90) welds only 1/16 inch wide in steel plate 1/2-inch-thick plate. Equipment of two types is available. One type uses accelerating voltages below 60,000 volts and the other uses accelerating voltages above 60,000 volts. The two types have characteristics which make them useful for a wide variety of work. In most electron-beam welders, the work is not a part of the electrical circuit, although it must be grounded.

Electron-beam welders are in effect X-ray tubes and produce X-radiation. Care must be taken to assure that personnel is shielded from this radiation.

Figure A-6 shows sketches of two electron-beam welding systems.

RESISTANCE SPOT, SEAM, AND PROJECTION WELDING

The heat required for fusion in these processes is obtained by the resistance of the parts being welded to a relatively short time flow of high-density electric current. The current is introduced into the parts by electrodes of one type or another. Force is applied through the electrodes to maintain contact between the parts to assure a continuous electric circuit and to forge the heated parts together. Normally a small amount of metal is melted at the faying surfaces of the joint. It is the coalescence of this melted metal which creates the weld. Spot welding is diagrammed in the sketch in Figure A-7.

A wide variety of equipment is used for resistance welding. Different types of current are used, although about 90 percent of commercial installations are 60-cycle alternating current.

The three types of welds are characterized by the following:

(1) Spot welds are individual welds whose shape and size is determined by the electrodes. A series of spot welds is usually used to make a joint.

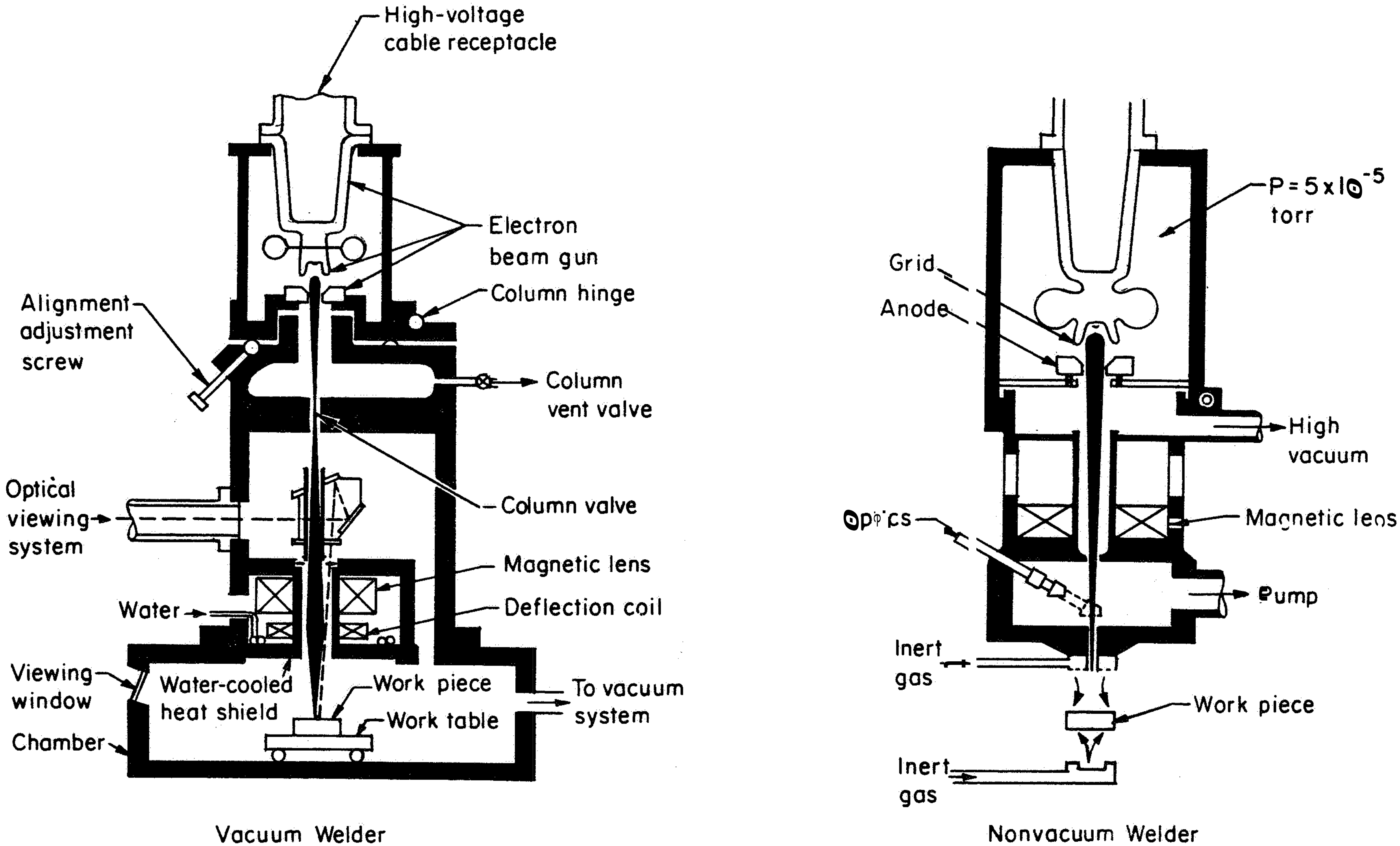


FIGURE A-6. SKETCHES SHOWING TWO TYPES OF ELECTRON-BEAM WELDING MACHINES

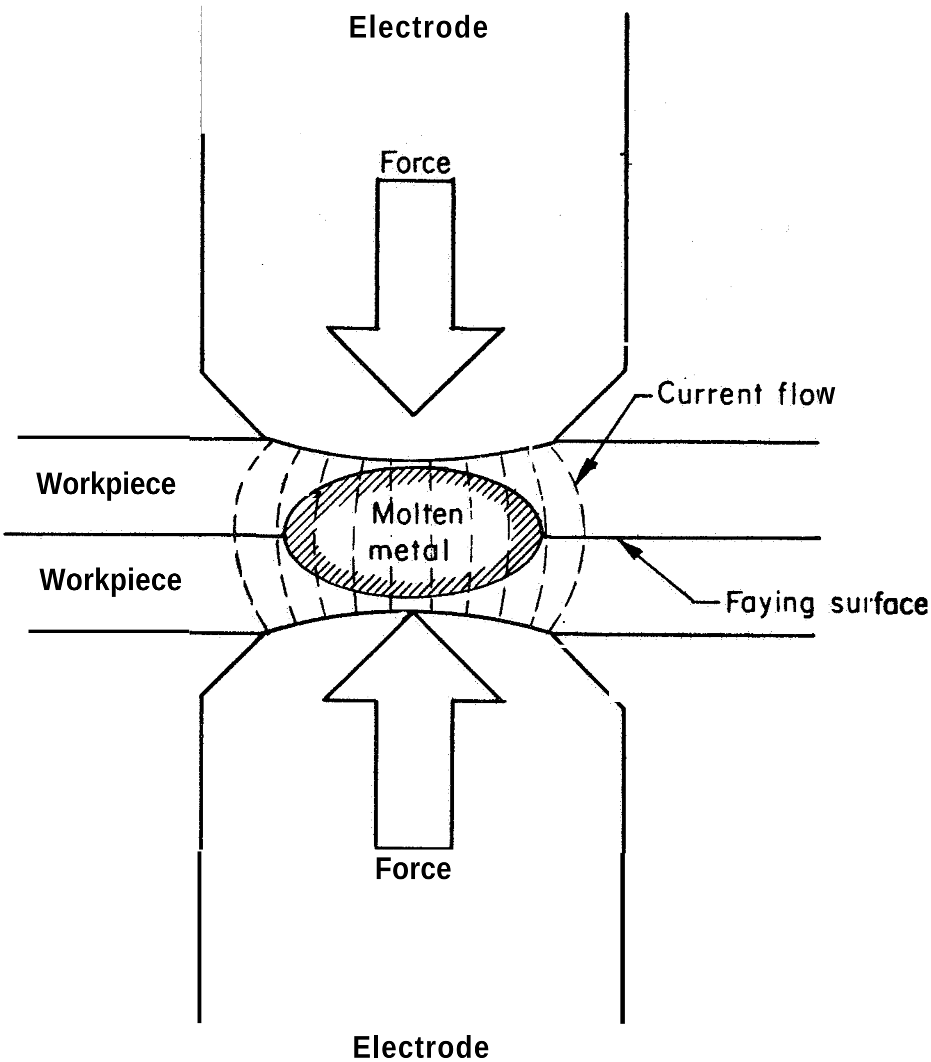


FIGURE A-7. SKETCH SHOWING ELECTRICAL FLOW AND HEAT GENERATION IN A SPOT WELD

(2) Seam welds are a series of overlapping spot welds made with circular rotating electrodes.

(3) Projection welds are spot welds whose location is determined by projections formed into the parts to be welded.

Sketches showing the basic characteristics of the three types of welding are shown in the sketch in Figure A-8.

FLASH WELDING

Flash welding is a butt-welding process in which the entire area of the surfaces to be welded are heated by a flow of electrical current across the joint. The flow of current produces a flashing action which is the fusing of contacting points of metal on the surfaces being welded. Flashing plus resistance heating melts the faying surfaces. When the proper temperature is reached, force is applied to upset the parts together. The upset squeezes out the molten metal and produces a solid-state weld. Flash welding is actually a solid-state welding process, although molten metal is involved in preparing the faying surfaces for welding. Figure A-9 is a sketch which shows the basic characteristics of the process.

BRAZING

Brazing is a process in which a filler metal having a melting point below that of the base metal is used to make a joint. The process is called brazing when temperatures above 800 F are required to make the joint. It is called soldering when temperatures below 800 F are used. Brazed joints normally have large areas and very small thickness. Fluxes may be used to clean and protect the joint area during heating. When fluxes are not used, rigorous precleaning and high-purity atmospheres are required to produce good joints. The filler

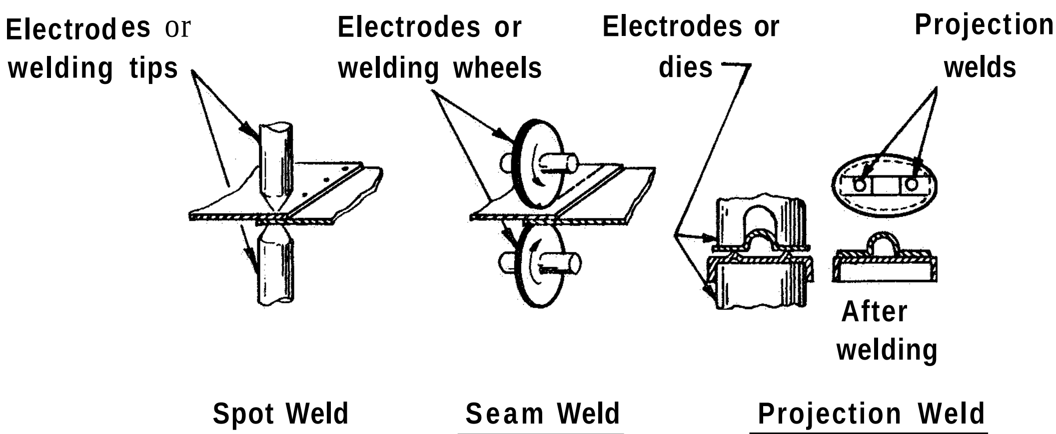


FIGURE A-8. SKETCHES SHOWING CHARACTERISTICS OF SPOT, SEAM, AND PROJECTION WELDING (Ref. 29)

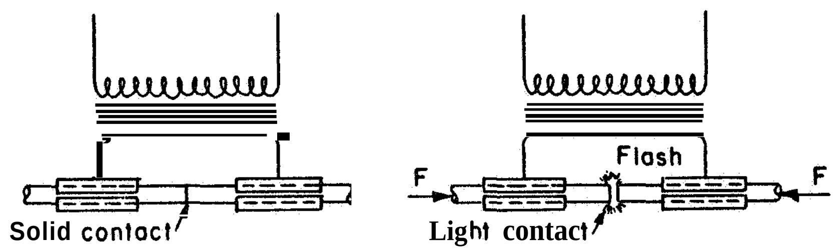


FIGURE A-9. SKETCH SHOWING BASIC CHARACTERISTICS OF FLASH-WELDING PROCESS (Ref. 20) metal is melted in contact with the joint area. Capillary forces cause the metal to flow into the joint. Because capillary forces are important in determining the extent and quality of the joint, it is necessary to provide and maintain proper clearances in the joint during the joining operation. Clearances of 0.002 inch to 0.005 inch are common. Smaller or larger clearances may prevent flow of the filler metal into the joint. With larger clearances, even preplaced filler metals may flow out of the joint when they melt.

SOLID-STATE WELDING

Solid-state welding includes any process where two or more pieces of metal are metallurgically joined without the formation of a liquid phase. A metallurgical joint is one in which the weld is the result of the action of atomic forces rather than mechanical interlocking. All solid-state welding operations require forces which press faying surfaces into contact with each other. These forces may or may not be high enough to cause gross upset. Solid-state welding is discussed in detail in Reference 62. Solid-state welding includes a number of processes, but they can be divided into two classes:

(1) Diffusion welding

(2) Deformation welding.

Diffusion Welding. In this type of solid-state welding, diffusion across the joint interface is primarily responsible for forming the weld. Only a small amount of deformation occurs during the process. Diffusion welding is done at elevated temperatures. This makes it easier to obtain the microplastic flow required to produce intimate contact of the faying surfaces and decreases the time required to obtain the amount of diffusion and grain growth required to complete the joint. Dissimilar metals may or may not be used in the joint to increase diffusion rates.

Deformation Welding. Deformation welding includes those processes in which gross plastic flow is the major factor in weld formation. Diffusion is not normally required for weld formation, although it may contribute if welding is done at elevated temperatures. The bonding mechanism with this process is not known precisely. It is generally believed that gross deformation breaks up the surface films which prevent intimate contact at the faying surfaces, forces clean surfaces into contact, and perhaps provides the energy needed to complete weld formation. Deformation welds are produced at temperatures from room temperature (cold welding of aluminum and copper) to temperatures just below the melting point (upset-butt welding of steel).

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APPROVAL

WELDING OF STAINLESS STEELS

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The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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